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# THE SOUDAN FORMATION AND A NEW SUGGESTION AS TO THE ORIGIN OF THE VERMILION IRON ORES.

JOHN W. GRUNER.

## INTRODUCTION.

THE Soudan iron-bearing formation and its hematite ores have been described by several investigators.[1] Some facts in part newly discovered, suggest that the history of the ore bodies may have been different from that assumed at present.

The Soudan formation occurs in Archean greenstone as steeply inclined folds and belts. The folding is so complicated that only in a few places have the structures been interpreted with any degree of certainty. The very numerous basic and acid intrusives of several geologic periods have cut the formation into many disconnected patches or belts. Around the hematite ore bodies these intrusives may be altered to "soap rock" which has been mistaken for greenstone older than the Soudan formation in cases where no detailed study could be made.

The individual belts of the iron formation are rarely more than a few hundred feet wide. But there are at places several narrower

1 Winchell, N. H., and Winchell, H. V., "Iron Ores of Minnesota," Geol. and Nat. Hist. Survey of Minn. Bull. 6, 1891.

Winchell, N. H., "The Geology of Minnesota," Geol. and Nat. Hist. Survey of Minn., vol. IV., Final Report, 1899.

Clements, J. M., "The Vermilion Iron-bearing District of Minnesota," U. S. Geol. Survey Mon. 45, 1903.

Van Hise, C. R., and Leith, C. K., "The Geology of the Lake Superior Region," U. S. Geol. Survey Mon. 52, 1911, pp. 118–143.

parallel ones separated by greenstone and intrusives of varying width and shapes. Along the strike one finds the same numerous interruptions.

MINERALOGY.

The belts consist of many bands and lenses of varying composition. Chert bands (now recrystallized quartz) alternate with magnetite, hematite, and amphibole bands. There is no rule as to their succession and size. The average thickness is about one half to one inch, though in some places they attain a thickness of several inches. The transition between iron oxide and amphibole and chert bands is sharp (see Fig. 1), which accounts for the well banded and striking appearance of the outcrops.

The Soudan formation contains in most places from 20 to 30 per cent. of iron. In some places this amount may decrease to only a few per cent. with a corresponding gain in silica. Probably half of all the iron is in the form of magnetite. Hematite may make up from 25 to 40 per cent. of the iron, while the rest is in amphiboles and carbonates. Pyrite, though hardly ever abundant, is widely distributed in the Soudan formation. Notwithstanding the great metamorphism the grain of the formation is very fine, and with the exception of quartz, not coarser than that of the Biwabik formation on the West Mesabi range. The iron oxides are so fine grained that polishing of specimens to a high luster is often impossible. On account of this fine grain usually no magnetic concentrate above 56 per cent. of iron could be obtained from material crushed to pass 150 mesh.[2]

Such a condition would not be suspected in the hand specimen where the minute particles of gangue in the very fine grained oxide bands can not be seen. This gangue remains attached to the magnetite in spite of the fine crushing.

[2] These tests were made by the School of Mines Experiment Station of the University of Minnesota. See Grout, F. F., "The Geology and Magnetite Deposits of Northern St. Louis County, Minnesota," Minn. Geol. Survey Bull. 21, pp. 76–81, 1926.

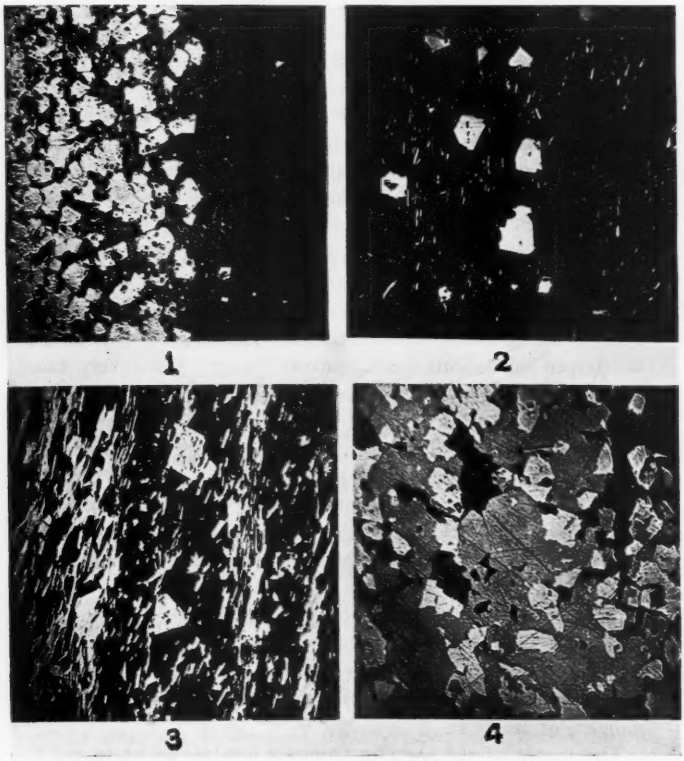


FIG. 1. Relatively sharp contact of magnetite-hematite layer and gangue layer (dark). Note small size of average magnetite grain. × 50.

FIG. 2. Magnetite euhedra and contemporaneous minute lath-shaped micaceous hematite crystals. × 100.

FIG. 3. Lath-shaped micaceous hematite crystals partly replaced by octahedra of martite. × 90.

FIG. 4. Intimate association of magnetite (gray) and contemporaneous hematite (white). × 340.

RELATION OF MAGNETITE TO HEMATITE.

A most striking feature of the two oxides is that they always occur together. In the majority of cases they seem to be contemporaneous. A common example is shown in Fig. 2. Minute lath-shaped micaceous hematite crystals surround magnetite euhedra. These two minerals do not cut each other. Fig. 3 shows the two again in different proportions. Euhedra of magnetite now martite) of all sizes cut the micaceous hematite in places. Another intimate relationship may be seen in Fig. 4, where the two oxides are intergrown. In some specimens the hematite may be in small grains in the magnetite. In the black jasper bands which get their color chiefly from very minute octahedra of magnetite a few hematite scales may be included. On the other hand, in the red jasper bands with much hematite "dust" a few very small octahedra of magnetite are practically always present.

In the ore may be seen well developed lens-shaped crystals of specular hematite and exceedingly dense fine grained areas of hematite which are either specular hematite or martite; probably both are present, but as the material does not take a good polish this is uncertain. Minute areas of magnetite may also be found in the ore. It is impossible to ascertain whether they are residual or younger than the hematite, for as has been already stated,[3] magnetite will replace hematite beginning near the center of the grain. Martite in the incipient stage of replacing magnetite along the octahedral structure planes seems to be almost absent. In practically all the martite found the alteration of the magnetite is complete or nearly so.

The shapes of the specular hematite crystals seems to tell us something of their history. In the Soudan formation, the ore bodies excepted, most of the hematite where subjected to regional

[3] Gilbert, G., "Some Magnetite-Hematite Relations," ECON. GEOL., vol. 20, p. 591, 1925.

Gruner, J. W., "Magnetite-Martite-Hematite," ECON. GEOL., vol. 21, pp. 375–393, 1926.

Dannecker, E. "Mineralogisch-mikroskopische Untersuchung der Erze und Nebengesteine des Magneteisenlagers 'Schöne Anfang' bei Breitenbach, Kreis Wetzlar," *Neues Jahrb.*, Beilage Band, 53, p. 201, 1925.

pressure shows the micaceous forms with large basal pinacoids. (See Figs. 2, 3.) In the ore, vugs and veins the hematite is lens-shaped due to the prominent development of flat rhombohedra.

### HYDROTHERMAL ACTION.

Though at many places intrusion of small porphyry masses has apparently produced no very marked effect on the iron formation, there are two or three places where alteration has been quite prominent. Half way between Tower and Ely near the west end of Armstrong Lake (Sec. 14, T. 62 N., R. 14 W.), just south of the new "Vermilion trail" highway there is an old prospect with an "ore" dump and a waste pile. (See Fig. 5.) About 75 feet

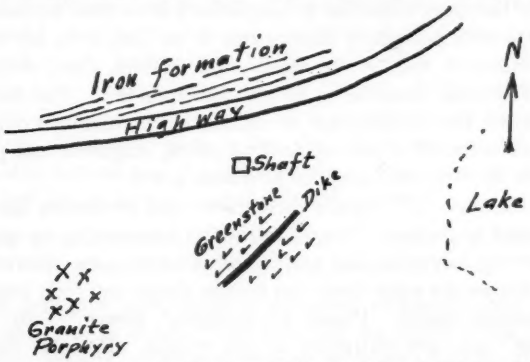


FIG. 5. Sketch of outcrops at magnetite deposit on Armstrong Lake.

north there are outcrops of the main belt of magnetic Soudan formation. A few small veinlets of calcite may be noticed in it. At the shaft greenstone schist intruded by a small unsheared hydrothermally altered dike (intermediate? composition) is found and 150 feet southwest there is granite porphyry related to Giants Range granite.

The ore on the dump is largely brecciated magnetite cemented by white calcite and some amphibole with possibly a little quartz. A little of the original magnetite still shows banding. Late magnetite in fine grains replaces portions of the calcite. Rela-

tively large amounts of pyrite, as the last mineral, in small crystals are sprinkled through the magnetite and calcite. There is enough pyrite to make the otherwise high grade magnetite non-merchantable.

The two outstanding facts are: Quartz has been removed almost completely. Calcite, magnetite, and pyrite have been introduced. These processes occurred along a foot wall of schistose greenstone intruded by dikes. The possibility that the leaching of silica was accomplished by descending cold waters long before the intrusion of the porphyries must be considered. In that case the result should have been limonite and ultimately hematite as in the Soudan mine to which such an origin has been ascribed. Even if there had been reduction to magnetite due to later intrusives, a phenomenon practically absent either in the ores or in the banded formation in spite of the numerous intrusions, there should be some specular hematite or its pseudomorphs left. The only explanation then is that due to contact effects and hydrothermal solutions the silica was replaced by calcite, magnetite and pyrite. In the thin sections examined no quartz is left.

That calcite will replace chert under such conditions has been reported by Butler.[4] The present writer believes that we are just beginning to realize that calcite and dolomite (for siderite this was known for some time) can replace almost any rock, even one containing quartz. Papers by Brögger,[5] Bowen,[6] Daly,[7] and Cooke[8] are very instructive in this respect. Probable replacements by carbonates on a large scale have come to the notice of the Minnesota Geological Survey also.

About 2,000 feet east of this deposit at the contact of the same belt of Soudan formation and the corresponding greenstone belt

[4] Butler, B. S., "A Suggested Explanation of the High Ferric Oxide Content of Limestone Contact Zones," Econ. Geol., vol. 18, p. 401, 1923.

[5] Brögger, W. C., "Die Eruptivgesteine des Kristianiagebietes," vol. 4, 1921.

[6] Bowen, B. L., "The Fen Area in Telemark, Norway," *Am. Jour. Sci.*, vol. 8, pp. 1–12, 1924.

[7] Daly, R. A., "Carbonate Dikes of the Premier Diamond Mine, Transvaal," *Jour. Geol.*, vol. 33, pp. 659–684, 1925.

[8] Cooke, H. C., "Kenogami, Round and Larder Lake Areas, Timiskaming District, Ontario," Can. Geol. Survey Mem. 131, p. 48, 1922.

the McComber mine has a shaft 400 feet deep which was full of water in 1923. The iron formation on the bluff just north of the shaft is identical with the one at the prospect just described. The waste dumps show the same schistose greenstone. The ore is chiefly brecciated magnetite covered by limonite. Some very fine grained hematite, apparently as original dense bands of iron formation, is present. Pyrite is quite abundant as crystals in the magnetite and as veins. Marcasite is also very common and easily recognized when in nodules. The limonite encrusts most of the magnetite and pyrite and cuts these minerals as veins. No martite was discovered in any of the polished sections.

The earlier history of the deposit is probably identical with that of the prospect just mentioned, but after erosion had brought the deposit close to the surface oxidation of the pyrite began. The acid waters attacked the calcite and in this way solution channels were produced along which portions of the magnetite could also be dissolved. Reprecipitation as limonite and marcasite followed. This took place before the present topography was established because now Armstrong Lake is only a few feet away from and almost as high as the collar of the shaft.

## CAN HYDROTHERMAL ACTION BE RESPONSIBLE FOR THE FORMATION OF THE HEMATITE ORES?

Few problems have occupied economic geologists more and have led to less satisfactory solutions than the origin of the great iron ore deposits. The concentration of some of them, as for example the Brazilian ores, have not been explained so far.[9] For others several hypotheses have been offered. In the Lake Superior region the cold-water leaching hypothesis, first advanced in detail by Van Hise, seems to explain the origin of the majority of the ore bodies better than any other hypothesis.[10] Difficulties may arise, however, when an attempt is made to explain all ore bodies in this way.

[9] E. C. Harder believes them original sediments without later concentration: ECON. GEOL., vol. 9, p. 106, 1914.

[10] For a synopsis on the origin see Lindgren, W., "Mineral Deposits," 2d edition, 1919, pp. 370–374.

On the Vermillion range there are ore concentrations of different ages. Some of them, as those at Soudan, have undergone much regional metamorphism. In the light of the evidence produced by Dr. C. J. Müller and given in footnote No. 33a, it is questionable whether the Soudan ores were much metamorphosed. To determine their origin would be much more difficult than that of the ore bodies of the "Ely Trough" which are younger.[11] No regional metamorphism or intrusions have occurred near them since their ore was formed. The Ely ores can not therefore be older than the end of the Lower Middle Huronian period, the last

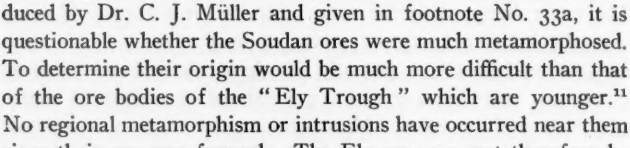


FIG. 6. Hypothetical conditions in Ely trough assumed for the discussion of the formation of the ore by cold descending solutions.

period of intrusion and folding of which there is any record. The bodies occur more or less disconnected in a trough, as it has usually been called, a very complicated structure, which only in recent years has been mapped in much detail by the Oliver Iron Company. The trough is over a mile long. Intrusives cut it in many places. Mr. J. F. Wolff, geologist of the Oliver Mining Company, was so kind as to supply the following recent information:

In the so-called "trough" there is a very large intrusive of basic porphyry cutting across the iron formation at a slight angle with the strike, the porphyry mass having a maximum width of 400 feet or more, as I recall it. From this there apparently are offshoots cutting into the iron formation and even back into the greenstone footwall, and there are also at least a few smaller acid porphyry dikes cutting iron formation, greenstone footwall and the large basic porphyry.

The dikes are usually altered almost beyond recognition. The ore bodies, as far as known, reach to a depth of at least 1,500 feet

[11] Van Hise, C. R., and Leith, C. K., Mon. 52, p. 142.

(2,000 feet at Soudan). There is a thick cover or roof of unleached Soudan formation on the ore in most places which is brecciated like the ore.[12]

The most conspicuous feature of the larger portion of the ore is its highly brecciated character; "soft ore," the miners call it. Rubble ore is a better term, since it really consists of hard, dense pieces of hematite derived from the Soudan formation and still showing banding in places. There is about 20 per cent. pore space in portions of the ore.[13] Secondary hematite as replacement mineral and as cement is very common. Micaceous hematite ore is absent. Magnetite, pyrite, calcite, chlorite, and quartz are also present in small amounts. At the east end of the trough the rubble ore becomes cemented by hematite, calcite, and siderite, and may be as hard as the ore of the Tower district.[14] The practically complete absence of limonite or other hydroxides of iron is an outstanding fact. There is only about 1 per cent. loss on ignition of the ore. Most of this is attributed to the driving off of $CO_2$.[15]

Assuming leaching of the Soudan formation by cold descending waters as has been advocated, we encounter unusual diffculties. Taking for granted, for the present, that large quantities of quartz (the chert is recrystallized) can be leached easily, even to great depth, we must account for the oxidation of the magnetite and iron in the silicates to hematite. We must also note that considerable iron has traveled some distance and finally as hematite replaced quartz. Since iron in cold solutions is carried in the ferrous stage, the transportation of it must have been one of the first processes in the Ely trough [16] before the iron minerals could be oxidized. This should have happened before much silica was leached, for according to earlier investigators the leaching waters contained oxygen on their downward journey. It is difficult to see, however, how very vigorous circulation of water could have occurred in the dense cherts before much pore space was available.

[12] Clements, J. M., *op. cit.*, p. 221.
[13] Van Hise, C. R., and Leith, C. K., *op. cit.*, p. 141.
[14] Clements, J. M., *op. cit.*, p. 233.
[15] Van Hise, C. R., and Leith, C. K., *op. cit.*, p. 139.
[16] Van Hise, C. R., and Leith, C. K., *op. cit.*, p. 539.

The precipitation of the dissolved iron by oxidation farther down in the trough is unexplainable, especially if it is necessary to assume little previous leaching at depth and a fairly high water table. Its deposition as iron carbonate in the bottom of the trough would have been possible, of course, but in view of the fact that with increase of hydrostatic pressure more $CO_2$ and consequently more iron can be held in solution, this assumption does not seem reasonable. Besides, this iron carbonate would have had to be oxidized later. The descending solutions are supposed to have transported a great deal of silica. Notwithstanding the various changes in the concentration of such constituents as $CO_2$ in the solutions which must have occurred, if we assume the solution, transportation, and reprecipitation of iron in the trough, the silica was not precipitated but removed entirely.

If, on the other hand, the water table had been depressed to the depth of the Ely trough (probably more than 1,600 feet below the then existing surface), there might have been sufficient oxidation but hardly the proper conditions and enough water to transport much iron and remove enormous quantities of quartz. In this connection the probability has not been mentioned before that ground water ordinarily[17] would become fairly well saturated with silica by its action on the numerous silicates in the soil and underlying rocks before it could collect in the troughs. All our experience and numerous experiments tend to confirm this probability. Quartz ordinarily, therefore, would be the *last* substance to yield silica to solutions.

In copper and lead-zinc districts where the water table has been depressed as much as 2,000 feet oxidation reaches to such depth locally in the sulphides. The writer can not find any case, however, where leaching of quartz by descending waters has occurred on any extensive scale even to a depth of 1,000 feet. Locally silica may be dissolved, but then there is usually evidence that silica is reprecipitated not far away.[18]

[17] Gruner, J. W., "The Origin of Sedimentary Iron Formations," ECON. GEOL., vol. 17, pp. 423–433, 1922.

[18] In this connection a recent paper by Dr. C. K. Leith on silicification of erosion surfaces (ECON. GEOL., vol. 20, p. 513, 1925) is instructive.

The mechanics of the circulation of ground water through troughs is also somewhat complicated. It is assumed that there is sufficient head to force the solutions out of the troughs at the lower ends. This has been illustrated by Leith[19] for the Mesabi range where the Virginia slate ponded the ground water. This special condition is lacking at Ely now. There is brecciated unleached iron formation on the deposits. The iron formation in the trough is cut by dikes in the most intricate manner. Some of them cut diagonally across and it seems would be very effective barriers to ground water circulation.[20] The large intrusives reach the present surface as far as known. According to Mr. J. F. Wolff:

> The greater the intrusives the larger the ore bodies. Folding alone has not given rise to any ore bodies—that is there are many jasper synclines surrounded by greenstone, of course, but in none of them are ore bodies found unless intruded by igneous rocks.

Let us assume for the sake of discussion that there are no dikes and that the trough had had an impervious layer of some formation on the top, as shown in the hypothetical diagram, Fig. 6. It is difficult to see why there would not have been relatively stagnant water in the bottom of the trough and circulation just below the impervious top layer. An outlet at the bottom of the trough is hardly possible in view of the impervious nature of the soap rock which encloses the ore and jasper.

The great mass of ore comes to the surface at only two very small places at the west end of the trough, according to J. F. Wolff, and it is well known that on the sides of the troughs the ore is at least several hundred feet below the surface. It extends into the overlying jasper as "fingers and balloon shaped masses of ore" (J. F. Wolff). Why should solutions move down the sides of the troughs for hundreds of feet without leaching, and then suddenly begin their activity?

[19] Leith, C. K., "The Mesabi Iron-bearing District of Minnesota," U. S. Geol. Survey Mon. 43, p. 266, 1903.

[20] The mine maps which have not been published are rather convincing in this respect.

Ordinarily where we find oxidized iron ores and gossans due to surface and ground water circulation, the oxidation decreases rapidly with depth or is rather spotty. Its greatest horizontal section is at or near the surface that existed at the time of oxidation. This condition has been especially emphasized for the Mesabi range. It certainly is one of our chief criteria for oxidation due to surface conditions and has been applied as such to almost all kinds of deposits which originated under widely varying climatic and structural conditions.

If arid or semi-arid climate is assumed during the leaching it is not clear to the writer why the relatively little water that seeped into the ground should have collected in large quantities in the Ely trough. There are many other troughs and structures around that could have diverted the flow. As a matter of fact, Van Hise and Leith [21] write concerning the Ely deposits:

> Here also parts of the formation are found separated from the main mass by greenstone masses in such a manner as to make it difficult to explain them on the basis of occurrence in troughs alone.

So far the absence of limonite has not been discussed. There certainly must have been much iron hydroxide if we assume cold water circulation with the accompanying reduction and oxidation. In some places in the Ely trough some limonite occurs in the so-called paint rock, but there it seems to be a very late product due to the decomposition of pyrite and some iron carbonate. It is not found in the ores derived from the jasper. In the Mesabi ores which probably formed in pre-Cambrian times, limonite is very abundant; why is it not at Ely, where no metamorphism has occurred since ore formation? This absence can not be explained by any possible burial of the ore bodies under a few thousand feet of sediments, for there are other ore bodies in the Lake Superior region that contain some limonite in spite of greater depth than the Ely deposits. Any dehydration due to burial should have also anamorphosed the highly decomposed dikes to some noticeable extent.

Now let us consider whether igneous emanations could have

[21] U. S. Geol. Surv. Mon. 52, p. 137.

been instrumental in the formation of the ore. As has been shown intrusives are present in large numbers, but can emanations from such rocks be sufficiently oxidizing to change magnetite to hematite?

Ordinarily we do not associate oxidation with such emanations, but there are many examples of such a process, on a relatively small scale. Martite which seems to be of thermal origin in most cases,[22] and specular hematite are of common occurrence in pegmatites, contact, and replacement deposits. Some examples on a large scale, where oxidation by far overbalanced reduction are Elba in Italy,[23] Striberg in Sweden,[23] Villa de Frades in Portugal,[23] Cerro de Mercado[24] and Sierra de Mercado[25] in Mexico, Eagle Mountain, California,[26] Iron Age deposit near Dale, California,[27] and Iron Mountain and Pilot Knob, Missouri.[28] Hematite makes up more than 90 per cent. of the total oxides of some of these. Large sections of the Gellivare and Svapavaara deposits of northern Sweden[29] consist of hematite. Also certain Cuban deposits could be mentioned in this connection.

The source of the oxygen in such reactions has been much discussed lately,[30] and though still unexplained, the fact remains

22 Wachtel, D. E., "The Origin of Martite." Unpublished thesis, University of Minnesota.

23 Beyschlag, F., Krusch, P., and Vogt, J. H. L., "The Deposits of the Useful Minerals and Rocks," 1914, pp. 366–382.

24 Farrington, C. L., "Some Notes on the Cerro de Mercado," *Eng. and Min. Jour.*, vol. 78, pp. 345, 1904.

25 Hill, R. T., "The Occurrence of Hematite and Martite Iron Ores in Mexico," *Am. Jour. Sci.*, vol. 45, p. 111, 1893.

26 Harder, E. C., "Iron Ore Deposits of the Eagle Mountains, California," U. S. Geol. Surv. Bull. 503, 1912.

27 Harder, E. C., and Rich, J. L., "The Iron Age Iron Ore Deposit Near Dale, San Bernardino County, California," U. S. Geol. Surv. Bull. 430, p. 231, 1910.

28 Crane, G. W., "The Iron Ores of Missouri," Mo. Bur. Geol. and Mines, vol. 10, 2d ser., p. 107, 1912.

29 "The Iron Ore Resources of the World," XI. Internat. Geol. Cong., Stockholm, 1910, pp. 570 and 577.

30 Butler, B. S., *op. cit.*, p. 398.

Sosman, R. B., "Oxygen and Volcanism," *Jour. Wash. Acad. Sci.*, vol. 15, p. 422, 1925.

Wells, R. C., "Chemistry of Deposition of Native Copper from Ascending Solutions," U. S. Geol. Survey Bull. 778, pp. 10–12, 1925.

that oxidation at depth due to igneous activity takes place under special conditions.

If we accept such oxidation for the ore in the Ely trough we may form a new picture of the origin of the ore bodies without encountering the obstacles enumerated above. It is true that ordinarily we associate hot ascending solutions with deposition of silica and not with its removal. There are cases, however, as was pointed out previously, where silica is replaced by carbonates. A conspicuous example of this type is also the Coeur d'Alene district of Idaho of which Ransome and Calkins write: [31]

> Large quantities of quartzite were replaced by siderite and if the dissolved silica was not deposited in neighboring fissures it must have been carried to a distance, since silicification is not a feature of the wall rock near the Coeur d'Alene lead silver deposits.

Emanations from silica poor magmas may be high in alkalies, alkaline earths and especially in $CO_2$ as has been pointed out by Bowen and Hewett.[32] These solutions must have a remarkable power to dissolve and replace silica without hindering the oxidation processes of iron to any appreciable extent, as is shown in the Rödberg iron district of Norway where *metasomatic* calcite and hematite ores occur together.[33]

A suggestion as to the origin of the Ely ore would be somewhat like this: Numerous intrusions brecciated the brittle Soudan formation throughout the trough. Ascending hot solutions oxidized most of the iron and dissolved and replaced quartz by secondary hematite, calcite, and dolomite, and on the east end of the trough in part by siderite. Some pore space may have been formed by leaching of quartz.[33a] The rising solutions were guided

[31] Ransome, F. L., and Calkins, F. C., "The Geology and Ore Deposits of the Coeur d'Alene District, Idaho," U. S. Geol. Survey Prof. Paper 62, p. 138, 1908.

[32] Bowen, N. L., *op. cit.*, pp. 6–11.

[33] Brögger, W. C., *op. cit.*, pp. 270–273.

[33a] It is difficult to form an opinion as to whether leaching by the ascending waters or replacement was more dominant in certain portions of the ore bodies. Dr. C. J. Müller of the Oliver Iron Company called the writer's attention to the finding of large vugs and cavities in the Soudan Mine. These cavities may reach the dimensions of a small room and are lined with beautiful large crystals of specular hematite, quartz, pyrite, and velvety chlorite. Usually they have paint

in part by the fractures, in part by the differences in composition and texture of the banded formation. The rising solutions were, of course, most effective near the bottom of the iron formation while still unsaturated with silica. In some deposits where the top of the ore seems to be exposed (for example at the La Rue mine on Armstrong Bay) it looks as if some of the quartz had been reprecipitated as coarse veins in the roofs of the ore bodies.

At a later date the carbonates were leached leaving the porous rubble. The solutions for this removal may have been of various origins and may have been active over several geologic periods. They could have been alkaline or saturated with carbonic acid without attacking the hematite. Even dilute sulphuric acid has little effect on hematite when cold as is well known. The leaching did not extend over the whole trough with the same vigor, for at the east end carbonates still cement portions of the ore. Slumping took place in the ore locally.

The same explanation of the origin of the ore may be advanced for the other Vermilion deposits, though with modifications since some of them have gone through a stage of anamorphism. It probably applies also to some deposits of the other Lake Superior ranges. On the Marquette range some ore bodies extend from the Negaunee iron formation into the overlying younger Goodrich quartzite along basic dikes which cut both formations.[34] These occurrences are hard to explain by the cold-water leaching hypothesis. Similar views as to the origin of the Vermilion deposits seem to have been developed contemporaneously by the geologists of the Oliver Iron Mining Company, who have made a very close study of these deposits during the past few years.[35]

rock as one of the walls and ore and jasper on the other sides. If the ore had been metamorphosed at Soudan (after formation by descending waters) the paint rock should have been squeezed into the cavities and metamorphism should have closed most of the pore spaces, as Dr. Müller pointed out to me.

[34] Van Hise, C. R., and Leith, C. K., Mon. 52, p. 272, and Fig. 36, *b*.

[35] Mr. J. F. Wolff wrote the author quite recently: "For your information, both Dr. Müller and myself are of the opinion, which I have held for a long time, that the Ely ores, and the Soudan ores also, have developed through the leaching action of thermal ascending waters, rather than meteoric waters together with deposition of secondary iron oxides, recementation of residual oxides thereby and consolidation of the ores by slumping."

## CONCLUSIONS.

1. There are on the Vermilion range no magnetic belts of Soudan formation extensive enough to become ore reserves by magnetic concentration except in the very distant future.

2. Most of the iron formation on account of the extremely fine grain of the oxides, does not make a magnetic concentrate higher than about 56 per cent. iron when crushed to pass 150 mesh.

3. Magnetite and hematite are practically contemporaneous in much of the formation. Martite occurs only in small amounts as far as can be ascertained by microscopic investigation.

4. Several small magnetite deposits originated by hydrothermal action in the Soudan formation whose silica was replaced by calcite, pyrite, and secondary magnetite.

5. In one of these deposits the pyrite was weathered. The descending acid waters dissolved the calcite and attacked the ferrous iron with the production of limonite and marcasite.

6. It seems to the author that the cold-water leaching hypothesis of the origin of the Ely ores does not explain very satisfactorily the absence of limonite, the removal of most quartz to great depth, the presence of calcite cement at the east end of the Ely trough, the practically complete oxidation of all iron to hematite in depth, and the brecciated but unleached thick cover of Soudan formation on the top of the ore. On the other hand, the intricate intrusions which cut up the trough into sections, and are intimately associated with the ore, the absence of deposits in troughs that show no igneous intrusions (but otherwise should be favorable for ore under the old hypothesis), the fingering out of the deposits upward into the brecciated iron formation, and the replacement of quartz by hematite, magnetite and carbonates suggest the following hypothesis: The numerous intrusives brecciated the brittle iron formation, hot solutions poor in silica but rich in $CO_2$ leached and replaced the quartz by hematite and carbonates at the same time oxidizing the ferrous iron of the iron formation to hematite. These solutions in part followed the bands of the iron formation, in part cut across them along brecciated zones. Later the carbonates were largely removed leaving a porous rubble ore.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.

# A BRIEF HISTORY OF THE OIL POSITION IN AUSTRALASIA.

A. E. BROUÉ.

THE first attempt to produce oil in Australasia was made in 1865 —seven years after Colonel Drake and the Smiths bored the first hole in Titusville, Penn. This first attempt was made in New Plymouth, New Zealand, and has been followed with more or less persistence for sixty years. At one period the flow from two wells was sufficient to cause a company to erect a refinery, but the supply of oil was not sufficient to keep it going and a few years ago the plant was sold to the Anglo-Persian Company and was dismantled.

Following the New Zealand activities, some enthusiasts bored at Roma, Queensland, Australia, and at one period a great outburst of petroliferous gas occurred. Catching fire by accident it destroyed the steel derrick in the space of twelve minutes. It was subdued after burning some fifty hours and later pipes were laid in the town for the purpose of lighting it, but the pressure suddenly ceased and the gas has not been tapped since. Roma is in the great Artesian Water Basin and the water influence therein is not yet completely understood. Mr. Henderson of the Queensland Mines Department condensed one and one third pints of benzine per 1,000 feet of gas from this bore, with a rough field apparatus.

Many reports of oil occurrences in Australia have been made, but most of them have been proved on examination to be iron hydroxide. In the State of Queensland some slight traces of petroleum have been found in water bores, but nothing of moment.

Much activity was occasioned by the exhibition of bitumen from the Kimberley Division of northwest Australia, and much money was spent by two companies in boring, but no success was achieved. After combining leases embracing three vast Carboni-

ferous areas in that district my associates and I proceeded to Europe and America with the report of Mr. Leo J. Jones, Assistant Government Geologist of the State of New South Wales, who had conducted a geologic expedition over part of the area and reported favorably thereon. English and Dutch geologists were frankly sceptical, but after much persuasion I induced Frederick G. Clapp of New York to come down and report.

Mr. Clapp left New York in November, 1923, and his engagement did not terminate until November, 1925. He certainly knows more of the geology of New Zealand and Australia than any other foreign geologist. After giving me his preliminary report on the province of Taranaki, New Zealand, he proceeded to northwest Australia and it did not take long to convince him that the prospects there were so very slender that he did not feel justified in continuing the examination. On the report of Dr. Wade who was engaged by the Commonwealth Government to report on the oil position in Australia generally, it is proposed, however, to put down three bores along the Fitzroy River to test ground, the Commonwealth Government contributing 50 per cent. of the cost.

In Queensland the Orallo Company has done considerable boring under the direction of two gentlemen—one local and one, Mr. Allen, an American. Bores have been drilled in New South Wales at Grafton, Scone, West Bargo and Penrith, but so far without any success.

While it is suggested that some oil companies are concerned in preventing the production of oil in Australia, no definite proofs are forthcoming that such is the case.

Considerable boring has been done in the State of Victoria, bores having been put down at Boula Boula, Torquay and in the Glenelg River vicinity, and in south Australia bores have gone down at Robe, Kingston and the Coorong, but all have the same tale to tell—" no oil."

In December of 1924, I engaged Chester Washburne of New York to examine certain territory on the east side of the Continent, but his report being confidential and the property of a com-

pany of which I am a director, it must stand over for a future article. At the present time the position is that Taranaki Oil Fields Limited, New Zealand, has a capital of $4,000,000 and, although it has abandoned its No. 2 well, it is still drilling in shale and approaching 5,000 feet, at Tarata. Work is proceeding rapidly on the east coast of New Zealand on a new site with No. 3 well, and great hopes are centered there.

The staffs of the Taranaki Oil Fields Limited are almost all American and much good work has been accomplished. I should like here to express my thanks to the professional men of America for their great assistance to me at all times. From Dr. George Otis Smith, Director of the U. S. Geological Survey, outward, I have always received the greatest consideration, and no question or problem has remained unanswered. The American geologists are one of the world's most unselfish bodies.

A. E. BROUÉ.

SYDNEY,
AUSTRALIA.

# THE PREPARATION OF POLISHED SECTIONS OF ORES.[1]

M. N. SHORT.

## INTRODUCTION.

METHODS of preparing polished sections of ores have been developed with great success in various laboratories both in this country and in Europe. Nevertheless, an inspection of the literature shows that the procedure of polishing varies widely as a result of having been developed more or less independently in separate laboratories. This lack of uniformity suggests possibilities of improvement through greater coöperation between the various laboratories of economic geology, many of which have worked out methods as yet undescribed. This article describes the methods of grinding and polishing opaque ores as worked out in the petrographic laboratory of the U. S. Geological Survey. The writer acknowledges his indebtedness to Messrs. F. S. Reed and J. L. Mergner for helpful coöperation and valuable suggestions.

The polishing of opaque minerals in the petrographic laboratory of the U. S. Geological Survey was initiated by Mr. F. C. Ohm in 1910. The procedure used was a modification of that described by Campbell.[2] The mistake was made of trying to polish sections of too great area and very few surfaces greater than 1½" in length were prepared after 1916.

Further improvements were introduced by F. S. Reed in 1916. The procedure followed that developed by R. E. Head, of the Bureau of Mines. A third step was made in the grinding process; the specimen was ground by hand on a glass plate for a

[1] Published by permission of the Director of the U. S. Geological Survey.

[2] Campbell, W., "Microscopic Examination of the Opaque Minerals," ECON. GEOL., vol. I., 1906, p. 753.

minute using 60-minute carborundum. The specimen was then polished as before on muslin, but levigated chromic oxide was used as a polishing agent instead of rouge. The results of this method of polishing were good but the process was tedious. For instance, it required between 30 to 60 minutes to polish pyrite. It was found almost impossible to remove all of the scratches on a muslin cloth.

Polished sections mounted in brass tubes of rectangular cross section by means of wax were first prepared by Prof. L. C. Graton in the Laboratory of Economic Geology of Harvard University in 1921. This procedure was introduced in the Survey laboratory by Mr. Edward Sampson in 1922. Sampson also found that commercial sealing wax was objectionable owing to a considerably admixture of filler which tended to break loose during polishing and thus scratch the softer minerals. He prepared a special sealing wax which has proved entirely satisfactory.

A further improvement introduced by Sampson consists in polishing first on canvas cloth using 600 carborundum powder, followed by an additional polish on muslin cloth using a specially floated carborundum powder. This treatment is especially effective on hard minerals such as pyrite and reduces the time required in polishing more than one half. The final polish is given on a horizontal lap covered with billiard cloth using magnesium oxide as a polishing agent. The procedure was first worked out by N. Sabsay at Harvard University and later introduced in the Survey laboratory. Credit for discovering the value of magnesia as a polishing agent is due to Dr. Hans Schneiderhöhn, of the University of Giessen.[3] Clarence S. Ross in 1923 found that oil possesses certain advantages over water in grinding thin sections of certain types of porous and friable rocks on a hand plate. This method was applied by Sampson to polished sections in 1925. Methods of impregnating and stiffening crumbly and porous ores before polishing were developed by Dr. Clarence S. Ross and the

[3] Schneiderhöhn, Hans, "Die mikroskopische Untersuchung undurchsichtiger Mineralien und Erze in auffalenden Lichte," *Neues Jahrbuch fur Mineralogie*, Beil. Bd. 43, p. 400, 1920.

writer. The use of aluminous cement as a mounting medium in place of sealing wax was introduced by the writer.

## DETAILS OF TECHNIQUE.

In the following outline the process of grinding and polishing is divided into twelve steps numbered consecutively. In the detailed description these numbers are placed after subject headings for convenience.

*Outline of Procedure.*

1. Removal of chip from hand specimen by chiseling or with diamond saw.
2. Impregnation with Canada balsam or bakelite; used only with very crumbly specimens which can not withstand first grinding. Omitted with most ores.
3. Grinding of flat surface with 120 carborundum (hard ores) or F carborundum (soft ores).
4. Second impregnation with Canada balsam or bakelite. Required of ores already impregnated in step 2; also with porous ores which were strong enough to permit step 3 without impregnation.
5. Mounting the section in brass tube. This can be omitted if desired.
6. Grinding with F carborundum.
7. Grinding with B. & L. 906 optical emery.
8. Grinding on hand-plate with Sira abrasive and Petrolatum. Used with hard ores.
9. Polishing on canvas covered lap with 600 carborundum. Omitted with soft ores.
10. Polishing on muslin-covered lap with 10-minute carborundum.
11. Polishing on muslin-covered lap with floated chromic oxide or rouge. Used in case step 10 is not successful in removing pits from minerals of high or medium hardness.
12. Polishing on billiard cloth with magnesia oxide or black magnetic rouge.

*Coarse Grinding* (1 and 3).—The desired fragment of the specimen is first chipped off by means of a cold chisel. Davy and Farnham advocate the use of a diamond saw.[4] Although this offers decided advantages, especially when a definite direc-

[4] Davy, W. M., and Farnham, C. M., "Microscopic Examination of Ore Minerals," New York, 1920, p. 2.

tion of surface is required, it is best to avoid its use when possible because of the cost and rapid wear when sawing hard minerals. A satisfactory surface can be prepared on a horizontal lap in a surprisingly short time. Ordinarily the surface prepared should not exceed one square inch in area. When the specimen consists of a large proportion of hard minerals such as pyrite, it is best to do the first rough grinding with 120 carborundum. This is continued until a surface of sufficient area is obtained. The specimen is then removed and carefully washed to remove adhering carborundum grit. The hands should likewise be cleaned carefully to prevent coarse grit from getting into the succeeding finer grinding material. When the section consists mostly of softer minerals and only a minor proportion of pyrite or other hard minerals, it is best to begin the grinding process with F carborundum, as the coarser grades tend to tear deep holes and gashes in the softer minerals. The speed of the coarse grinding laps is 1,150 revolutions per minute.

Corners and projections of the specimen should be ground off in order to avoid excessive grooving of the surface by fragments breaking loose during the succeeding stages. It is advisable to bevel back the edge of the surface at least 60° from the face, as the mounting medium is more or less viscous and would have greater difficulty in flowing under a flatter beveled edge. The beveling is best done by holding the chip against the side of a fast rotating carborundum or emery wheel. In the absence of this, it can be done on the horizontal lap.

*Impregnation* (2 and 4).—When the ores are porous and crumbly, the grains tend to work loose before they are completely polished, and when carried across the face of the specimen, groove and scratch it. This may be avoided by filling the pore spaces with some binding medium that is carried into the pore spaces by capillarity or under a vacuum. The binding medium must be dissolved in some fluid of low viscosity in order that the resulting solution can readily enter the pores. The section is heated sufficiently to evaporate the solvent, leaving the binding medium in the pores.

As impregnation is most effective at the periphery of the specimen it is advisable to give a flat surface to the specimen before it is impregnated. Some specimens are too crumbly to permit grinding even a rough flat surface. With such ores it is advisable to give a first impregnation to the chip before grinding and a second impregnation afterwards.

The technique of impregnation with bakelite varnish has already been described by Clarence S. Ross [5] who developed the method as used in making thin sections of friable rocks. In the paper in Economic Geology a method of impregnating specimens with bakelite under a vacuum is described.

The procedure described by Ross is highly successful with polished ores. The specimen is immersed in a dish containing the solution of bakelite with ether and alcohol or ether and acetone and the dish is covered to prevent too rapid evaporation of the solvent. The bakelite solution is drawn into the pores of the specimen by capillarity. After four to eight hours the cover is taken off the dish and the contents exposed to the air over night. The solution is then about the consistency of unthinned bakelite or possibly still thicker. The specimen is then removed from the dish, and placed with its flat side uppermost in a warming oven. Care should be taken to have a generous coating of the solution on the surface and to keep the surface flat so that the solution will not run off. At the end of 48 hours the bakelite is usually entirely cured. It is futile to attempt to hasten the process of curing bakelite. The application of too much heat or a too rapid increase in the heat will cause its decomposition and the formation of bubbles which tend to blow out material already in the pores.

The excess bakelite is then ground off the surface on a horizontal lap using F carborundum. It is then examined under the microscope. If necessary the entire process can be repeated, as cured bakelite is not affected by the solvent used. The second

[5] Ross, Clarence S., "A Method of Preparing Thin Sections of Friable Rocks," *Amer. Jour. of Sci.*, Series 5, vol. VII., 1924, p. 483; "Methods of Preparation of Sedimentary Materials for Study," Econ. Geol., vol. 21, pp. 454–468, 1926.

impregnation is usually not necessary, however, as bakelite holds the mineral grains firmly, and a specimen with 50 per cent. of its pore spaces filled with bakelite will take a satisfactory polish.

Impregnation of specimens with Canada balsam was accomplished by the writer in the Laboratory of Economic Geology of Harvard University in 1922. The specimen was boiled in xylol for about two hours, then immersed in a pan containing a solution of balsam and xylol in equal parts. The pan was heated and the xylol slowly driven off. When the solution was viscous enough to harden completely when cooled, the specimen was taken out. This procedure is fairly successful and can be used in the absence of a vacuum apparatus, but it is open to the following objections:

1. Fumes from boiling xylol are objectionable and it is difficult to prevent their escape. Xylol being rather highly volatile, a good deal is wasted in boiling. On the other hand, long boiling is necessary to exhaust the air. A container for boiling xylol should be air-tight and connected to a condensing apparatus.

2. Diffusion which is the process relied upon for getting balsam into the pore spaces is almost inoperative when the xylol-balsam solution begins to get viscous.

To meet these objections as far as possible the present practise is to exhaust the air in the pores by means of a vacuum apparatus. An aspirator connected to a water faucet is inexpensive—not more than $3—and gives a high vacuum. Between the aspirator and the vacuum jar is a bottle which acts as a trap to prevent water from getting into the vacuum jar; the apparatus is thus rendered nearly "fool-proof." An open-tube mercury pressure manometer is connected with the bottle. (See Fig. 2.) (Caution: When the proper vacuum is reached close the water tap *last* in order to prevent the water from rushing back into the apparatus.)

The object is to get as much balsam into the pores as possible. Consequently a proportion of balsam to xylol should be used to yield the maximum usable viscosity.

The soft balsam of commerce contains much turpentine that

requires a relatively high temperature for its elimination. The removal of xylol from a xylol-balsam solution is accomplished at a much lower temperature. Hence the turpentine should first be distilled off before the balsam is dissolved in xylol. The turpentine is boiled out by pouring the balsam into a shallow pan and heating on an electric hot plate. The proper time to remove the pan can be determined only by repeated trial. A thin rod or nail is dipped into the fluid and pulled out leaving a long thread of the material. If this snaps on cooling, the balsam in the pan will likewise be brittle and ready for use when cooled.

A solution of 40 grams of hard balsam in 60 cc. xylol is poured into a flat-bottomed glass dish that contains a coarse wire screen at its bottom so that the fluid may reach the flat face of the section placed face down in the dish. The dish is then placed in the vacuum jar and the air exhausted. The manometer is not absolutely necessary but indicates when the exhaustion of air has gone as far as it will. A vacuum registered by a 71 cm. column of mercury is reached in the apparatus described (approximately 76 cm. registers a perfect vacuum at sea level). Ordinarily this does not require over 15 minutes. The aspirator requires a pressure head of at least 75 feet of water for its efficient operation.

The specimen is then removed from the vacuum jar and placed face-down (again on a flat screen) in an iron pan containing a solution of approximately equal parts of xylol and balsam. The pan is placed on a hot plate and the xylol slowly driven off. The proper time to remove the specimen is determined by trial as already described. The balsam should be syrupy when hot and hard and brittle when cold. The specimen should be removed while the balsam is still hot but not so hot that all the syrupy balsam will drip off the face when the specimen is removed. It is best to let the balsam cool until a fairly thick coating will adhere to the face of the section when this is removed from the pan. When cold the excess balsam is ground off, using F carborundum.

Only one impregnation is applicable since hard balsam already in the pores is still soluble in a xylol-balsam solution. As already stated, bakelite once hardened is inert chemically. The

chief advantage of balsam over bakelite is the fact that a balsam impregnation can be prepared in an hour or less, whereas bakelite requires three days. On the other hand, bakelite is harder than balsam and holds the grains of a specimen with a firmer grip.

*Mounting* (5).—The chip already surfaced and leveled is mounted in a section of rectangular brass tube. The tubes are 1½ in. x 1⅛ in. outside dimensions and cut in ⅞ in. lengths. The brass is .039 in. thick. These tubes are furnished by the American Brass Company, Waterbury, Connecticut, and cost approximately three cents a section. Before mounting, three conical indentations are punched in each of the longer sides of the tube (Fig. 1) to prevent the mounting medium from slipping in

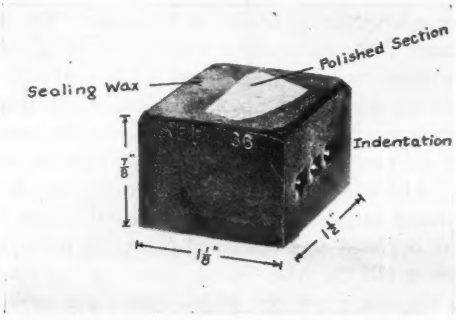


FIG. 1. Mounted polished specimen.

the brass. These indentations are driven in with a steel center punch and, to prevent inward bulging of the tubing, it is placed over a slotted steel bar.

The number and other designations of the specimen are stamped on the shorter side of the brass tubing by means of a hammer and 3/32" dies. Usually an abbreviation of the locality is given followed by a number, thus DU 30 represents No. 30 of the Ducktown collection. The tube is supported while being stamped by a steel bar similar to the preceding but without the triangular slot.

When mounted in sealing wax, the section and tube must first be warmed to approximately the temperature of the molten sealing wax, otherwise the sealing wax will shrink away from the walls of the tube on cooling. When the tube is warmed before pouring the sealing wax, the shrinkage of the brass is greater than that of the sealing wax and thus fits tightly to it.

The warming is done in an electric oven 11 in. x 11 in. x 14½ in. in size manufactured by the Central Scientific Company, Chicago. It is equipped with a thermostat for maintaining a constant temperature. A steel plate 9½ in. x 10 in. x ¼ in. with one machined surface supports the sections and their mounts. A cardboard is placed on the steel plate and the section is placed face-down on it. The brass tube is placed over the section in such a way as to center the section in the mount. The steel plate is then placed in the stove and a temperature of approximately 100° C. is maintained for five minutes. The steel plate is withdrawn from the stove and the molten sealing wax is then poured into the brass tube until it just reaches above the indentations. When cool the cardboard is easily removed from the mount.

Sealing wax tends to flow during hot weather and it has been found advisable to give the wax a backing of plaster of paris. The section is placed face-down and plaster of paris poured in until it almost fills the tube, leaving about ⅛″ of clearance in order that the mount will rest on its brass edges when righted.

A sealing wax made according to the following formula:

120 gm. flaked shellac,
90 gm. resin,
60 cc. turpentine,

has been found entirely satisfactory. The ingredients are placed in a "granite-ware" sauce pan approximately 5½ in. diameter and 2½ in. deep, and the pan placed on an electric hot plate (a Bunsen flame or small electric stove will serve the purpose). Heating is continued until vigorous bubbling sets in, the mixture being stirred from time to time by means of a tablespoon. When thoroughly mixed the pan is removed and the mixture

stirred until it ceases to bubble. If the sealing wax is too hot when poured, bubbles tend to form after pouring. Those on the surface of the mount, *i.e.*, adjacent to the polished surface, are objectionable in that they tend to collect grit during the subsequent grinding and polishing.

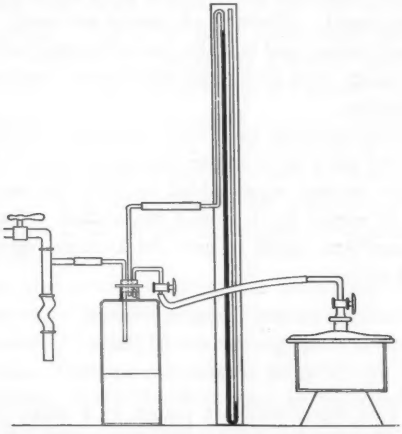

FIG. 2. Vacuum apparatus for impregnating with balsam.

The advantages of sealing wax are:

1. It can be prepared easily and a section can be mounted in a few minutes time.

2. It takes a good polish and does not collect grit.

3. It wears away a little faster than the ore and allows the latter to come into good contact with the polishing medium.

4. It is satisfactory in appearance.

Its disadvantages are:

1. It requires the application of heat and a somewhat involved manipulation of the brass tube and section before pouring.

2. It requires a second mounting medium (plaster of paris) to give it proper backing.

3. It will not stand any subsequent heat treatment such as that required for impregnating porous or crumbly ores.

A large number of experiments involving cold mounting media were tried out. Ordinary Portland cement proved unsatisfactory. When used pure it tended to shrink and crack in a few days. It is not hard enough for use until at least seven days old, and in two weeks it is so hard that it stands out in relief above the soft sulphides and prevents good contact between ore and polishing agent. Mixtures of cement and sand, cement and limestone, and cement and talc also proved unsatisfactory. Most of these mixtures were sticky and claylike and required tamping around the section.

A satisfactory medium was finally obtained. It consists of a mixture of 7½ parts of Lumnite cement to 1 part of plaster of paris and just enough water added to allow the mixture to be poured and to mould itself around the section. The following quantities have been found to give the average requirement for one polished section:

15 gm. Lumnite cement,
2 gm. plaster of paris,
9 cc. water.

The first two ingredients are placed in a sauce pan, stirred until thoroughly mixed and the water then added. The mixture is again stirred until of a uniform consistency. Enough material to mount 20 sections can be made in one mixture.

The specimen is placed face-down on a smooth glass plate on which has been rubbed a very thin coating of vaseline or graphite grease. The tube is placed over the section and the cement mixture poured in until the tube is nearly full. A tablespoon is more convenient than pouring directly from the pan.

The glass plate must not be moved until the first set of the cement takes place, as the tube slides very easily on the greased surface. The first set requires about three hours, after which the glass plate is placed in a pan containing sufficient water to submerge completely the section. After 24 hours the plate is taken out of the water and the mounted section removed from the plate. It is then ready for the final grinding and polishing.

The grease gives a glazed surface to the cement and permits the easy removal of the mounted section from the plate.

Lumnite cement is manufactured by the Atlas Lumnite Cement Company, 25 Broadway, New York. It contains a high percentage of aluminum which gives it the quick-hardening properties. When used alone it tends to shrink on setting, forming numerous cracks. Plaster of paris counteracts this shrinkage tendency. A mixture of 2 parts of Lumnite cement to 3 of plaster of paris expanded so much that it ruptured the brass tube.

*Fine Grinding* (6).—The mounted section is ground on a horizontal lap using F carborundum. The inequalities of the mounting medium are worn down and the entire surface is made perfectly plane. The grinding should be continued until the pits and scratches made by the coarser abrasive are removed. Usually one minute suffices.

The edges and corners of the brass mount are beveled on a carborundum wheel in order to avoid tearing the cloth during the polishing process, (See Fig. 1) and to prevent the specimen, through suction, from adhering to the grinding lap.

*Fine Grinding* (7).—The next stage in the grinding process is accomplished on a horizontal lap using Bausch and Lomb 906 optical emery. The pits and scratches made by F carborundum are ground out. Thirty seconds usually suffices for this stage of the grinding process. The speed of the fine-grinding lap is 1,108 revolutions per minute. If the section is composed largely of softer minerals it is ready for polishing.

*Fine Grinding* (8).—If the specimen contains hard minerals it is best to grind by hand on a glass plate for one minute using Sira abrasive and oil. Sira abrasive is manufactured by R. & J. Beck, 68 Cornhill, London, England. It consists of a well-sized platy artificial corundum and is free from coarser grit. Liquid petroleum has been found more satisfactory than water for hand grinding.

*Polishing* (9).—The section is given a first rough polish on a horizontal lap covered with canvas using 600 carborundum as a polishing medium. 6 oz. duck has been found satisfactory. The

than chromic oxide and is less effective with hard minerals like specularite. Both rouge and chrome generally leave a series of fine scratches which are removed by magnesia. The speed of the polishing lap used in this and the following stage is 1,481 revolutions per minute.

*Polishing* (12).—The final polishing is accomplished by means of either magnesia or "black magnetic rouge" on a horizontal lap covered with billiard cloth. The technical or trade name of this cloth is Samson cloth and it is supplied by J. Magann and Company, 78 Washington Street, Boston. Magnesium oxide or magnesia is effective in polishing pyrite and minerals of intermediate hardness. It also gives a good polish to softer minerals but tends to form more scratches than black magnetic rouge. Magnesia is mixed with about 2 parts by volume of water and blown out of a wash bottle. Schneiderhöhn advises keeping the bottle tightly stoppered, as the magnesia tends to absorb carbon dioxide from the air, forming magnesium carbonate which scratches the softer minerals. Magnesium oxide actually has a greater hardness than the carbonate but breaks down in polishing to an exceedingly fine state of subdivision. Magnesia will remove fine pits as well as scratches from pyrite. Five minutes or less usually suffices to give a perfect polish to pyrite. Additional time is sometimes advisable when polishing some minerals such as marcasite which are primatic in habit and more or less porous. The writer has spent as much as 15 minutes to good advantage. Magnesia is ineffective in polishing specularite and some other minerals of equal or greater hardness and it is not advisable to carry the process beyond the chromic oxide stage.

"Black magnetic rouge" is a polishing powder manufactured by Binney and Smith, 41 East 42d St., New York. Its use was recommended to the Survey by Prof. Alan M. Bateman. According to the manufacturers it is obtained by a patented process of precipitation and consists of 99 per cent. $Fe_2O_3$. In general its effect is the same as magnesia but it does not cut as fast. It is the best medium for polishing soft minerals such as galena and chalcocite. It is more stable than magnesia and does not deterio-

rate when exposed to the air. It is mixed with a small proportion of water and applied to the cloth by means of a small paint brush. When used wet it will remove practically all the scratches, but in spite of care to prevent contamination by extraneous grit, a few scratches will persist however long the polishing is continued. If the section is to be photographed, these last scratches can usually be removed by the following procedure which was developed by F. S. Reed:

Apply moist magnetic rouge to the rotating lap, press the specimen very lightly against it giving the specimen a slow rotation. Continue until the lap is entirely dry. Some skill and experience is required in manipulation. If dry polishing is continued too long the specimen tends to overheat. If underpolished the magnetic rouge tends to gum up and adhere to the specimen. This process is not recommended except for photography as there is a tendency for the mineral to smear.

The following table summarizes the characteristics of the abrasives as observed under the microscope. The size was measured by means of a micrometer occular. Size is given in millimeters.

| Abrasive | Size of Largest Grain Observed | Size of Most of the Material | Characteristics |
|---|---|---|---|
| 120 Carborundum..... | .291 | .156 (average) | Angular and well sized. |
| F Carborundum..... | .26 | .052–.104 | Angular and well sized. |
| 600 Carborundum..... | .135 | .02–.04 | Contains considerable proportion .06, also much fines, poorly sized. |
| 65 Alundum..... | .075 | .004–.01 | Contains a considerable proportion of grains .025, also much fines, poorly sized. |
| 906 Optical Emery.... | .043 | .011 (average) | Very well sized. |
| Sira..... | .026 | .0037–.018 | Very thin plates, some perfect hexagons, others more or less disc shaped. |
| 10-min. Carborundum (prepared in Survey Laboratory)..... | .03 | .0015–.003 | |

conditions and the gases contained in them differ physically and chemically. There are 20 folds in the Bighorn Basin that yield gas. The reservoir rocks of these pools are of six different geological formations that range in age from late Pennsylvanian to upper Cretaceous. In several folds gas produced from neighboring wells differs in chemical and physical properties, consequently

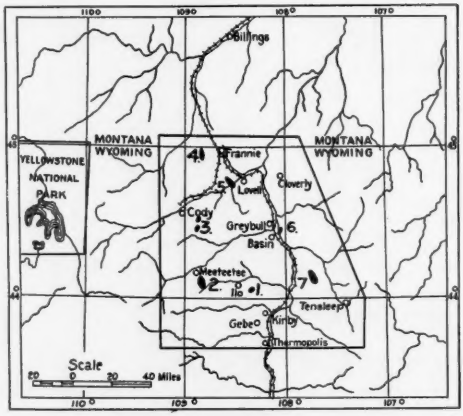


FIG. 1. Sketch map. Bighorn Basin and main gas fields.

1. Golden Eagle.
2. Buffalo Basin.
3. Oregon Basin.
4. Elk Basin.
5. Byron.
6. Lamb.
7. Hidden Dome.

it is hoped that significant deductions regarding geological associations and controls may be reached from a study of this region. Should certain features be found common to the gas-bearing and source rocks of all gas fields, then those features must have a bearing on the origin and associations of natural gas; other conditions common to many fields will no doubt be found and local geological phenomena will explain the minor variable features.

During the first season's field work on this problem (1924), the writer studied the Oregon Basin Gas Fields in the northern

part of the Bighorn Basin.[1] In 1925 the Golden Eagle and other fields were studied and it was concluded that the Golden Eagle gas originated in beds of continental accumulation. This exceptional conclusion is opposed to the usual conception that commercial quantities of petroleum products originate in marine strata, and for that reason a brief discussion of the field is of interest.

The writer is indebted to Mr. L. L. Bechtel, Superintendent of the Midwest Refining Co., Grass Creek, Wyoming for logs of the wells; to Mr. Victor Cotner for aid in mapping the field; and to Mr. R. M. Templeton for surveyed plats of T.45 N., R.97 W; and to Dr. T. W. Stanton, of the United States Geological Survey, for his corrections of stratigraphy, especially of those parts dealing with the Mesaverde and Meeteetse formations. The writer wishes to thank Professor Alan M. Bateman for many helpful criticisms and suggestions in preparing this report.

## GENERAL FEATURES AND DEVELOPMENT.

The Golden Eagle field is situated in T.45 N., R.97 W., Hotsprings County, Wyoming in the "Blue Mesa" quadrangle of the United States Geological Survey. The first reference to the field in the geologic literature was published in 1921.[2] The areal geologic map of Wyoming [3] shows at this locality a window of the Lance formation surrounded by Fort Union beds, thereby indicating the presence of an anticline. The writer found no Lance strata on the apex of the anticline, which is, however, correctly located on the above-mentioned map.

Development of the Golden Eagle field started in the fall of 1919, although the first well to be started was not completed until December 7, 1923. This delay can in part be attributed to a fire that destroyed the rig and in part to a change in the ownership of

[1] The results of this study were used by the writer as a dissertation presented for the doctorate degree at Yale University.

[2] Richardson, G. B., and Heald, K. C., U. S. Geol. Survey map. "Oil and Gas Fields of the State of Wyoming." 1921.

[3] Campbell, M. R., and other members of the Geologic Staff, U. S. Geol. Survey map, 1925.

the land. The well yielded four shows of gas between 2,442 and 2,560 feet and made 5½ million cubic feet per day under 700 pounds rock pressure at 2,665 feet. The log of this well to 2,270 feet was burned, but Mr. Berry, who worked on the well, told the writer there were two small shows of gas at a depth of about 1,600 feet. Gas struck at about 2,100 feet was responsible for the fire.

A well (No. 4) was started on February 12, 1920, but was not drilled to the gas-bearing horizons. A third well (No. 3) started on May 10 of the same year obtained a first show of gas at 1,640 feet. Fifteen more shows were encountered between 2,070 and 2,955 feet, and then a flow of 20 million cubic feet per day under 1,125 pounds rock pressure came from 2,980 to 3,000 feet, the total depth of the well.

A deep test well (No. 1 Lander Permit No. 018319) was drilled in the summer of 1922. Shows of gas occurred at eight horizons, the shallowest being 1,610 and the deepest, which also yielded the most gas, at 3,055 feet. Five of these shows were found between 2,102 and 2,376, but not one gave commercial production and the well was plugged at a depth of 4,019 feet.

The field was developed by the Wyoming-Yellowstone Oil Company, but in 1922 was bought by the Midwest Refining Company.

## STRATIGRAPHY.

The stratigraphic section of the Bighorn Basin includes pre-Cambrian to Eocene sediments. However, only those formations penetrated by drilling on the Golden Eagle field will be discussed here. They are limited by the Cody shale, penetrated for a few hundred feet by the deep test well, at the base, and the Fort Union formation at the top.

*Cody Shale.*—The Cody shale includes 2,000 feet of dark greenish-blue marine shale largely of Niobrara age. The upper part of the Cody is sandy, is brown to buff in color, and contains, in the southern part of the Bighorn Basin, a fairly persistent sandstone member that is correlated with the Shannon sand of the

Salt Creek oil field. This horizon was reached in the deep test well, but was barren of oil and gas in the Golden Eagle field.

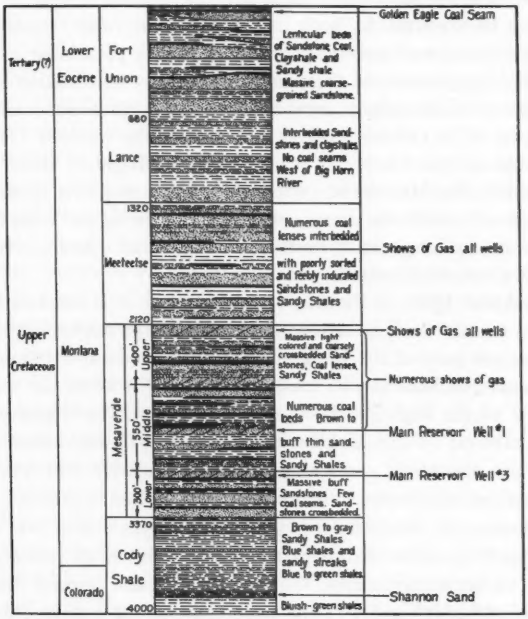


FIG. 2. Sketch of stratigraphic column. Golden Eagle Field.

In the northern part of the Bighorn Basin the upper part of the Cody shale is of Montana age.[4] No marked lithologic change indicates the position of the Eagle sandstone, and no Eagle fauna was found in these beds where they crop out a few miles southwest of the Golden Eagle field. Lupton[5] named this group of sediments for the town of Cody, about 50 miles north of the area under consideration, where the entire formation is freshly exposed in the Shoshone River Gorge.

[4] Heald, K. C., personal communication.

[5] Lupton, C. T., U. S. Geol. Survey Bull. 621, p. 171, 1916.

*Mesaverde Formation.*—The Mesaverde formation, of Montana age, includes about 1,250 feet of buff to white sandstones with several workable coal seams and interbedded brown to gray shales. In contrast to both the young and older strata, the Mesaverde are well indurated and give rise to prominent ridges. Hewett [6] in 1914 named these beds the "Gebo" formation from the town of Gebo, where excellent outcrops occur about 12 miles southeast of the Golden Eagle field. In the later work by Hewett and Lupton [7] the "Gebo" formation of the Bighorn Basin was referred to the Mesaverde formation, named and first described by Holmes,[8] which was in southwestern Colorado, and afterward applied to similar rocks in northwestern Colorado, and in central and southern Wyoming.

The lower limit of the Mesaverde formation is marked by a 45-foot massive buff sandstone that weathers in marked contrast to the upper part of the Cody shale. Three general divisions of the Mesaverde beds can be made throughout most of the southern part of the Bighorn Basin and especially in the ridges south and southwest of the Golden Eagle field: (1) the lower part about 300 feet thick, consisting chiefly of massive and coarsely cross-bedded sandstones, buff to gray in color and containing minor amounts of intercalated brown shaly layers and a few thin coal beds;[8a] (2) the central part about 550 feet thick, mainly of brown to tan sandy shales, thin sandstones, and several locally mined coal beds;[9] and (3) the upper part about 400 feet thick, predominantly sandstones, light buff to white in color, coarsely cross-bedded, containing enormous deep-reddish-brown concre-

[6] Hewett, D. F., U. S. Geol. Survey Bull. 541, p. 100, 1914.

[7] Hewitt, D. F., and Lupton, C. T., U. S. Geol. Survey Bull. 656, p. 26, 1917.

[8] Holmes, W. H., U. S. Geol. and Geog. Survey Terr. Ninth Ann. Report, p. 244, 1875.

[8a] Further north in the Bighorn Basin where a decided lithologic change occurs, from greenish clay shales of Cody age into massive sandstones, an Eagle fauna exists immediately above the sandstone beds. This feature was found by the writer in the Oregon Basin and Garland areas, but was not encountered where similar beds were studied in the southern part of the Bighorn Basin.

[9] On the crest of the Sand Draw anticline about 6 miles southeast of the Golden Eagle field, eight coal lenses occur in this zone. The thickest is seven and a half feet and the thinnest three feet.

tions that are sandy, but with interbedded gray shales and minor amounts of coal. The top of the formation is marked by a thick cross-bedded white sandstone that forms prominent ridges and is overlain by younger beds of poorly indurated buff to brown sandstones, with much interbedded shale and occasional layers of reddish-black lignitic coal. Although the Mesaverde formation varies slightly in thickness from place to place, it is about 1,250 feet in the southern part of the Bighorn Basin.

Abundant fossilized wood, coal, carbonaceous shale, as well as complete absence of marine forms indicate that the Mesaverde formation accumulated under conditions of continental sedimentation. It is believed that Mesaverde time is represented further north in Wyoming and in southern Montana by beds of Claggett and Judith River age. This means that the Mesaverde formation of the southern part of the Bighorn Basin accumulated over broad lowlands bordering the shallow epeiric seas of a part of Montana time. The writer spent considerable time in searching the Mesaverde beds near the Golden Eagle field for evidence of marine strata but found none.

*Meeteetse Formation.*—Overlying the Mesaverde formation are a group of from 700 to 750 feet of poorly indurated brown to buff sandstones, several carbonaceous horizons that locally become sufficiently carbonized to form high grade sub-bituminous coal, and layers of gray to brown shale. Poor sorting, inferior cementation, the occurrence of fresh biotite flakes in the sandstone beds, and the numerous coaly horizons are characteristic of this group of strata. Hewett [10] named these beds the Meeteetse formation after the town of Meeteetse, and the type locality is about 20 miles north of the area under consideration.

The Meeteetse is entirely of Montana age and apparently spans the time occupied in the accumulation of the Bearpaw formation to the east and north in Wyoming. That the Meeteetse beds represent continental accumulations in the lowlands bordering the Bearpaw sea seems probable. Hares [11] found Bearpaw fossils in his study of the Elk Basin field, 60 miles north of Golden

[10] Hewett, D. F., U. S. Geol. Survey Bull. 541, p. 102, 1914.

[11] Hares, C. J., U. S. Geol. Survey Bull. in preparation.

Eagle, that occurred in " the approximate equivalent of Hewett's Meeteetse formation."

Unconformable relations with the older Mesaverde beds are apparent just west of the Oregon Basin about 25 miles north of the Golden Eagle field, but were not found southwest of the field where the writer examined the contact.

*Lance Formation.*—Apparently conformable with the Meeteetse formation is a group of from 600 to 650 feet of buff to greenish sandstones and gray, brown, and purplish clay beds. This series was named the " Ilo formation " by Hewett [13] in 1914 for the excellent exposures just northeast of Gwynn's Ranch (formerly the Ilo settlement) about 4 miles northwest of the Golden Eagle field. Subsequent work by Hewett and Lupton [14] definitely established the age of the " Ilo " formation as Lance, since it contains numerous Triceratops remains. These strata are therefore now correlated with the Lance formation named by Stanton [15] for the exposures on Lance Creek in Niobrara County, Wyoming. They are readily separable from the older Meeteetse formation west of the Bighorn River by the absence of coal seams. The thickness of the Lance and the Meeteetse beds determined by the writer across section 23, T.45 N., R.97 W. is 1,440 feet.

*Fort Union Formation.*—Uncomfortable on the Lance formation is a thick succession of fairly well indurated buff to white sandstones, gray, purple, red and greenish clay beds, and numerous coal seams that occasionally are thick enough to be mined. These strata are correlated with the Fort Union formation named and first described by Meek and Hayden [16] for the exposures at old Fort Union, two miles southwest of Buford, North Dakota.

Although the unconformity is only locally apparent in the Bighorn Basin, a decided lithologic change marks the base of the Fort Union. Hewett [17] in his work on the Grass Creek, Mee-

[13] Hewett, D. F., U. S. Geol. Survey Bull. 541, p. 103, 1914.

[14] Hewett, D. F., and Lupton, C. T., U. S. Geol. Survey Bull. 656, p. 27, 1917.

[15] Stanton, P. W., *Am. Jour. Sci.*, 4th Ser., vol. 30, p. 172, 1910.

[16] Meek, F. B., and Hayden, F. V., *Proc. Acad. Nat. Sci. Phila.*, vol. 13, p. 433, 1862.

[17] Hewett, D. F., U. S. Geol. Survey Prof. Paper in preparation. Also personal communication.

teetse, and Oregon Basin quadrangles collected numerous fossils from below and above the basal sandstone member; in most instances identifications by Stanton showed the older forms as "Triceratops horizon" and the younger as "Fort Union." Conglomerate layers are frequently encountered at the base and in them are smooth and partially rounded pebbles the size of apples. Such a conglomerate marks the base of the Fort Union just south of the Grass Creek field a few miles west of the Golden Eagle field. The conglomerate facies was not found in section 23, T.45 N., R.97 W., where the writer studied the beds. Here a 40-foot, well indurated, angular grained, white sandstone forms a ridge in contrast to the gently sloping terrane developed on the older Lance beds. This sandstone was followed northwest along the strike until small quartzite pebbles were found in it. Still further along the strike it joined sandstones that Hewett[18] had assigned to basal Fort Union. Most of the sandstone and other beds above the base are extremely lenticular; on the southeast end of the Golden Eagle field a buff sandstone containing large rounded deep-brown sandy concretions was found to pinch from a thickness of 68 feet to only 15 feet in a horizontal distance of 300 feet along the strike. In this particular sandstone fossilized logs up to eight feet in length and a foot in diameter are quite common and several thin small-pebbled lenses occur. Hewett[19] measured 2,700 feet of Fort Union northeast of Gwynn's Ranch, the top being marked in this section by a bed of conglomerate 150–200 feet thick containing reworked Fort Union material that upholds the southwest crest of the Blue Mesa and is correlated with the basal part of the Wasatch formation.

The writer measured the section of the Fort Union from the base of the formation to the axis of the syncline southwest of the Golden Eagle field and determined the thickness to the 1,105 feet. Northeast of the syncline to the apex of the field 495 feet are exposed so that the top structure is 610 feet stratigraphically above the base of the Fort Union formation.

[18] *Ibid.*
[19] *Ibid.*

## WELL LOGS.

Ordinary logs are not sufficiently accurate to locate formation boundaries in the stratigraphic section penetrated in the Golden Eagle field. Furthermore, it would be burdensome to incorporate the complete logs of the three wells that reached the producing horizons. However, a few features given in the logs bear out the writer's deductions as to formation depths and thicknesses, and for that reason will be mentioned.

The base of the Fort Union formation should be apparent in the logs since it marks the most decided lithologic change in the upper part of the section penetrated. The shallow parts of only two logs (well No. 4 and No. 1 Lander Permit) are known but in each of these, this hard sandy horizon is fairly well shown. The log of well No. 4 records 125 feet of light gray sand from 485 to 610 feet and the log of well No. 1 Lander Permit records 89 feet of "hard drilling" sand, sandy shale, boulders and shell from 586 to 695 feet.

By extrapolation from the computed stratigraphic position of the wells on the surface it was found that No. 1 well should penetrate the upper part of the Mesaverde formation at 2,050 feet, No. 3 well at 2,060, and No. 1 Lander Permit at 2,160 feet. No. 3 well log records a 40-foot gray, medium hard, sand from 2,030 to 2,070 feet and No. 1 Lander Permit well log records 90 feet of hard gray sand starting at 2,085 feet. The log of well No. 1 was burned to a depth of 2,270 feet, and hence that part of the section including the top of the Mesaverde was lost. Well No. 4 was not drilled deep enough to strike the upper part of the Mesaverde.

Well No. 1 Lander Permit was the only one drilled through the entire Mesaverde formation. From surface computation the base should have been reached at 3,410 feet (2,160 plus 1,250). The log of the well is in close accord with this prophecy since at 3,395 feet the character of the sediments recorded is similar to that observed at the outcrop of the basal part of the Mesaverde formation.

This section of the log is incorporated since it illustrates the lithologic changes noted at the outcrop of the upper part of the Cody shale and the basal part of the Mesaverde formation.

PART OF THE LOG OF WELL NO. 1 (LANDER PERMIT NO. 018319).

| | | | | |
|---|---|---|---|---|
| 40 feet.....sand | dark gray | hard | 3,355–3,395 | dry, sharp. |
| *Base of Mesaverde Formation.* | | | | |
| 5 feet.....shale | light gray | medium | 3,395–3,400 | |
| 10 feet.....sand | gray | hard | –3,410 | |
| 20 feet.....shale, sandy | light | medium | –3,430 | |
| 20 feet.....shale | light blue | medium | –3,450 | |
| 30 feet.....shale, sandy | light gray | medium | –3,480 | |
| 120 feet.....shale | dark blue | medium | –3,600 | muddy. |

The producing horizons of the Golden Eagle field were determined by extrapolation from surface measurements. Mention has already been made of the depths from which shows of gas occurred and also where main production was encountered. Having found that the well logs are in agreement with the computed formation depths and thicknesses, it is apparent that the producing zones can also be located accurately from the logs.

The shows of gas from about 1,600 feet in the three wells drilled at least that deep must have come from a sand near the top of the Meeteetse formation. The next deeper horizon that produced gas is the upper part of the Mesaverde formation. No. 1 well had a show of gas from about 2,100 feet, No. 3 well from 2,070, and No. 1 Lander Permit at 2,102 with a stray showing at 2,008 that must have come from the lower part of the Meeteetse beds.

Main production from well No. 1 came from 2,665–2,676, the middle part of the Mesaverde formation, and several shows of gas were also encountered a little higher in the same part of the formation. The main production from well No. 3 came from 2,980–3,000, the upper beds of the lowest part of the Mesaverde and 15 shows of gas were encountered from the same formation above this. The largest flow of gas in well No. 1 Lander Permit was encountered at 3,050 feet, the upper beds of the lowest part

of the Mesaverde. This horizon closely approximates the sand that produced 5½ million cubic feet of gas in well No. 3 at 2,980 feet but was not reached in well No. 1.

The absence of productive horizons in wells No. 3 and No. 1 Lander Permit corresponding to the 2,665-foot sand of well No. 1 must be ascribed to the lenticular nature of the sandstones and the positions of the wells with respect to the folding. This will be discussed in more detail later (see under Natural Gas, Reservoir Beds).

## STRUCTURE.

The Bighorn Basin is a structural as well as a depressional basin. Not only do the strata dip gently from all sides towards the center but the Basin is surrounded on three sides by high mountain ranges and the fourth side is partly enclosed by the Pryor Mountain uplift, a huge faulted anticlinal flexure. In many places around the margins of the Bighorn Basin the strata have been folded, thus giving rise to anticlines and synclines superimposed on the regional dip that ordinarily would be toward the center of the depression.

Along the southwest side of the Bighorn Basin the usual dip of the strata is toward the northeast but in section 12, T.45 N., R.97 W. a gently dipping and slightly elliptical shaped dome has been formed, known as the Golden Eagle gas field. The Fort Union beds dip away in all directions from the center of the southwest quarter of section 12, T.45 N., R.97 W. and give rise to a dome with 405 feet of closure. The steepest dips occur on the northeast side of the field where angles up to 13 degrees are manifest but usually the dip is much gentler and averages about 5 degrees.

A pronounced syncline bounds the Golden Eagle structure on the west and south but it dies out to the north in the northwest quarter of section 11, T.45 N., R.97 W. and is not apparent east of the southeast quarter of section 18, same township and range. The strata dip more steeply on the south side of this syncline than on the north and angles as steep as 21 degrees are common in

the beds that crop out in section 23, T.45 N., R.97 W. (Fig. 3).

No faults were found by the writer while mapping the field. Faulting is, however, so common a feature in all Wyoming fields that it seems quite probable that the Golden Eagle has been

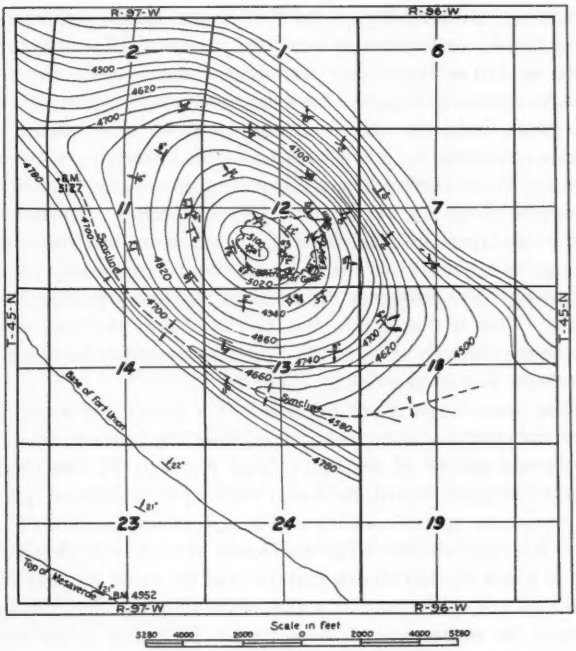


FIG. 3. Structure contour map. Golden Eagle Field. Contours drawn with 40-foot interval on the Golden Eagle Coal Seam. Elevations are based on sea level.

slightly faulted. At two places in the northwest quarter of section 12, T.45 N., R.97 W. weathering has formed surface conditions that look as though faulting had shattered the strata but

at neither locality could any dislocation be found. These two areas are the only places on the entire dome where even suggestive evidence of faulting was found and hence it is concluded that the field has not been faulted.

A brief description of this surface phenomenon is not out of place although it is not, strictly speaking, a structural feature. There are, within many of the Fort Union sandstones, layers of deep brown, well indurated sand that vary in thickness from less than an inch to four inches over short distances along the strike. Where coulees and gulleys have dug their channels through such sandstone beds, the valleys formed have, in many places, thin plates projecting for a few inches over the underlying softer material. With continued erosion, these plates break off and fall into piles along a lower level of the small valleys. Hence when indurated layers are plentiful within a sandstone bed and erosion has quite deeply incised the bed, the pile of fragmentary chips is augmented and resembles the effect of shattering produced by a fault. This is the case in two of the coulees that are cutting headward through some of the Fort Union sandstones along the northeast side of the Golden Eagle field.

The dome was mapped by means of a transit and stadia rod. Vertical control was carried by level from the bench mark in the northwest quarter of section 11, T.45 N., R.97 W. and checked at the last point located, the bench mark in the southwest quarter of section 23, same Township and Range, where an error of only 5½ feet was shown. The horizontal control was checked at many places by steel section markers and the error was too small to be plotted. The base of a coal seam (Fig. 2) that crops out around the entire crest of the dome has been used as the datum plane. This seam is named the "Golden Eagle coal seam." This layer is about 660 feet stratigraphically above the base of the Fort Union formation.

## NATURAL GAS.

*Kinds.*—The Golden Eagle gas is extremely dry; it contains a relatively high nitrogen content, but no hydrocarbons heavier

than methane and hence no gasoline. An interesting point for speculation arises from the nitrogen content of the gas from the two producing wells. The gas from the shallower reservoir contains 3½ times as much nitrogen as the deeper reservoir gas. Possibly the greater pressure in the deeper reservoir is the control regulating the nitrogen content but nitrogen being of such an inert character the writer doubts that pressure alone could account for the differences in composition. A more probable explanation is that there existed some chemical difference in the source materials. For example, if the source matter of the shallower reservoir contained a greater amount of animal remains than that from which the deeper gas originated, these nitrogenous remains might readily cause differences in the nitrogen content of the two pools. Another explanation might be advanced: Separation of the gases present in an initial single reservoir according to their relative specific gravities is possible. Should this reservoir then be connected with one higher topographically this new formed reservoir would contain a higher per cent. of lighter constituents than the deeper pool. Such a theory can be applied to the Golden Eagle field only if the nitrogen content of the two reservoirs contain helium, or some undetermined light gas, since nitrogen is heavier than methane. It is the writer's belief that the Golden Eagle gas contains a small amount of helium but it is contrary to government regulations to report inert gases other than nitrogen.

Other characteristics of the gas are adequately shown by the analyses. The writer took samples of gas from each of the producing wells and the following analyses were made by the Bureau of Mines, in Washington.

ANALYSIS OF THE GAS FROM THE GOLDEN EAGLE FIELD.

| | Well No. 1 | Well No. 3 |
|---|---|---|
| Carbon dioxide | 0.19% | 0.67% |
| Oxygen | 0.48 | 0.48 |
| Methane | 94.90 | 97.34 |
| Ethane | 0.00 | 0.00 |
| Nitrogen | 4.43 | 1.51 |
| Total | 100.00 | 100.00 |

*Quantities.*—The potential open flow of the Golden Eagle field was 25½ million cubic feet per day. This capacity never was attained because No. 3 well had fallen off before No. 1 well produced. However, the field was capable of producing from 15 to 18 million cubic feet per day for a short time. In July, 1925, the potential production was less than ¾ of a million cubic feet per day. Such a short life of the field is natural since the reservoir beds are thick porous sandstones that would give high initial production but would exhaust rapidly, and the areal extent of the field is small.

RESERVOIR BEDS.

Sandstones in the middle and lower divisions of the Mesaverde formation are the main reservoir rocks of the Golden Eagle field. It is from the middle zone that No. 1 well produced 5½ million cubic feet per day; and from the upper part of the lower zone that No. 3 well produced 20 million cubic feet and No. 1 Lander Permit gave the largest show. No. 1 well yielded small production from the upper division and four shows in the middle division. No. 3 well had 15 shows from the upper and middle zones and No. 1 Lander Permit had five shows in the upper sandy part of the formation. It is apparent that most of the gas was produced from the Mesaverde beds.

A few other shows deserve mention since they suggest local generation of small quantities of gas in beds younger than the Mesaverde. Well No. 1 is reported to have yielded two shows at approximately 1,600 feet, well No. 3 log records a show at 1,640 and a show in well No. 1 Lander Permit came from 1,610 feet. All of these small reservoirs are situated about at the base of the Lance or top of the Meeteetse formation. That they could be connected with the main reservoirs seems impossible. Such a great thickness (1,200 feet) of impervious clays and interbedded sandstones separate the two that migration could not have brought the gas up without leaving numerous other "show" sands and such were not found. Furthermore, the field so far as known includes neither fissures nor faults that might have acted as channelways for upward moving gas.

It is rather singular that the reservoir that produced a large amount of gas (well No. 1 at 2,665 feet under 700 pounds rock pressure) yielded only shows of gas in the other two wells that penetrated the horizon. A possible explanation of this condition is that the lower reservoir was the only one occupied by gas in an early stage of the field's history but as folding progressed with consequent fracturing of the apex, much of its gas moved upward into higher sands to form the shallower pool. The above explanation further demands that the original rock pressure must have been at least 1,125 pounds but with the escape of a great quantity of gas to the upper sand, equilibrium in it necessitated only 700 pounds pressure.

It is recognized that less pressure in the shallower reservoir, which is the condition found, is to be expected but differences of 425 pounds per square inch for differences in depth of only 400 feet imply abnormal conditions and necessitate special explanation. The possibility that there was a generation of gas from a source supplying only the upper reservoir must not be overlooked and it is the writer's belief that such a condition occurred, since the most likely source of the gas is contained in the coaly materials of the Mesaverde formation and these beds are interbedded with the reservoir sands. It is not possible that the two main reservoir beds with their different pressures are at present connected by an open channel. Hence either different source beds or establishment of a seal between the two reservoir beds in the past is essential to explain the facts. That the gas found in the shallow sand was originally in the deeper one, and under the same pressure found in the deeper sand, is possible. This explanation, however, does not suit the geological associations of the field in which the most probable source material is in close proximity with the reservoir beds. Hence it is concluded that the different reservoir beds received gas from different source beds. Before entering a discussion of the source beds, the generation and subsequent migration of the gas may be considered briefly.

## GENERATION AND MIGRATION OF GAS.

There are three separated and distinct periods during which the gas could have formed, although it seems more probable that generation continues throughout all of them. First, the gas could form during the accumulation of the beds; second, it could form during the consolidation of the beds, and third, it could form during the folding of the strata into their present structure. This last period may be divided into several parts according to the history of the deformation of the beds. For example, source materials that under initial stresses generate a liquid petroleum may later have this liquid transformed into gaseous matter by subsequent crustal movements. Such a theory might be advanced to explain the lack of oil in many gas fields, especially where two or more periods of folding have occurred.[20] In all events these times of gas generation are all included in the geochemical or dynamochemical stage of the formation of petroleum.

If generation accompanies accumulation, great quantities must escape to the air although large amounts may be expected to lodge in the associated loose materials. With subsequent change to a consolidated form, this gas will seek refuge in porous beds, being carried there by moving water and also being attracted to areas of least pressure. Consolidation of sands requires less squeezing than that of muds. With later folding of these strata, the gas would be forced into the crests of anticlines in accordance with Daly's[21] diastrophic theory for the migration of petroleum. If generation of the gas accompanies the change from unconsolidated materials to consolidated rocks, it is expected that lodgement will be in porous beds and later movement should be caused as postulated above. If generation occurs only during the folding of the strata, the gas will be forced into porous beds first,

[20] This theory was used by the writer as a possible reason for there not being oil in the Oregon Basin Gas fields where the geologic history of the region indicates two distinct times of folding. The most logical explanation of such oil-free gas pools and the one preferred by the writer is that natural gas has a source material or other substance that is distinct from the source material yielding liquid hydrocarbons.

[21] Daly, M. R., *Bull. A. I. M. E.*, No. 115, pp. 1137–1157, 1916.

since here a release of pressure is possible, and later to the places where these beds are upfolded. No one will deny that in the crests of upfolds, transmitted rock pressure is less than elsewhere in folded strata.

It is known that marsh gas generates in the unconsolidated matter at the bottom of many lakes. It is also known that lignites and other coaly materials when heated give off occluded gases as well as gases yielded by the breaking down of some of the carbonaceous materials. Hence it appears that generation of hydrocarbon gases may occur at all stages in the development of a pool. The writer favors the theory that the greatest generation of natural gas must accompany the deformation of the strata. It is during this period that the source materials are subjected to their greatest stress and heat. In the extraction of oil from oil shales, quantities of gas are liberated, when the shales are heated, and some oil shales yield liquids when subjected only to pressure.

Petroleum geologists are not agreed regarding the possible extent of lateral migration which will fill a fold with gas. Some claim lateral migration measured in miles is possible and others believe the distance must be limited to a few hundreds of feet. Hence it does not seem out of place to discuss here at some length the problem of lateral migration of gases. The following points will be considered in order: (1) the causes affecting movement, (2) the kinds of strata favoring movement, (3) the distribution of the source beds and its effect on lateral migration, (4) the quantities of gas generated in respect to the volume of porespace of the reservoir beds, and (5) the effect of lateral migration on the pool (transverse migration, nature of the reservoir bed, and size of the collective area).

*Causes Affecting Movement.*—Experiments have been made in an effort to discover the forces that cause movement of petroleum in rocks. Most of this work has sought evidence regarding the actions of oil but in some of the experiments gases have been used. The forces thus far considered to cause movement of oil into the most porous part of rocks are surface tension, capillarity, differences in specific gravity of oil and associated

water, the tendency of gas particles to rise or move to areas of less pressure and carry with them tiny films of oil, and the flow of water set up by squeezing the water out of unconsolidated beds during their consolidation. Subsequent movement of the oil within the porous rocks themselves has been attributed to moving water that has carried the oil along, or to flowing set up by gas movement to areas where release of pressure is possible. It is certain that where gas is concerned the forces acting will be in most part due to the nature of a gas (the tendency to expand since the molecules are not securely bound together and the extreme difference in specific gravity between a gas and a liquid) by which the movement will always be to an area of less pressure. This area in turn will be the highest part of a fold in rocks filled with water under hydrostatic pressure. Furthermore, it will be in a porous bed since in such pore spaces there is a release of pressure over the original impervious layers that most probably represent the source beds. That much gas can be held in fine-grained rocks with small pore spaces is well known, but this is not the case when the gas is under high pressures. To sum up, the forces tending to cause migration of gases are first, a flow of some liquid that will carry the gas, second, the large differences in specific gravity between a gas and liquid that cause the gas to rise, and third, the tendency of a gas to expand and hence seek areas where release of pressure is possible.

*Strata Favoring Movement.*—The kinds of strata concerned play a leading rôle in the migration of gas. It is conceivable that gas can migrate through very fine-grained and fine-pored rocks if they are dry. In dry rocks of this physical nature no water movement can inaugurate a flow of gas, but the nature of gases will probably cause a slow upward movement or migration. If fine-grained and fine-pored rocks are water-bearing, movement of gas will much more probably be around them since water clings so tenaciously to capillary openings. Furthermore, conditions in nature would offer channels of movement for gas that required less energy to be expended in acquiring this movement than in overcoming the great adhesion of water for capillary pore spaces.

Hence, if the extremely fine-pored rocks are water-bearing it appears unlikely that gas will migrate through them. For clayey shales, movement of gas must be extremely slow, but is possible. A few gas wells of southern Colorado produce commercial amounts of gas from this type of shale but never under high pressure, or with high volume yield, although they are consistent producers over long periods of time.

Hence the remaining kind of strata, course-grained and unless completely cemented, also course-pored, offer the most favorable conditions for migration. It must be through such rocks that migration takes place since in most experiments dealing with the migration of petroleum, as well as in gas and oil fields, it is from this type of rock that production occurs.

For gas to move readily through course-pored rocks it is necessary to have either a flow of liquid, or the existence of an area where there is less pressure, and the latter determines of course the flow of liquid. There are several areas where release of pressure can occur, for example the highest part of a lenticular bed of course-pored rocks, the crest of anticlines or domes, the location of faults or fissures that offer channel ways of escape, and the horizons where transverse movement into other coarse-pored beds occur, provided of course these are affected by less pressure.

If a fold is initiated in beds that contain gas and also above these beds there are impervious layers, it is to be expected that the gas will migrate for considerable distances and fill the area of the crest of the fold. Should subsequent changes in the water table cause underground movement in an opposite direction there might be a loss of gas from the crest of the fold due to flushing. It is even possible that later movement would entirely remove the gas originally segregated, but such underground movement of water would of necessity be towards a region of release of pressure. The normal case of sluggish movement could only be expected to reduce the gas volume slightly.

If gas has migrated through coarse-pored beds and accumulated in pools, it is essential that conditions of equilibrium occur after the migration is completed. This requires that the pool caused

by migration along one bed be under the same pressure and in one connected body; different pressures would be impossible unless a later crustal deformation or sedimentary activity (such as an increase in cementation) occurred. It can be stated then that had lateral migration been effective over long distances, the pool so gathered would be continuous and under a constant pressure, provided no subsequent changes had occurred. Hence it appears most probable that in a gas pool where different beds serve as reservoirs and different pressures are apparent in them, widespread lateral migration did not play an active part in accumulating the pool. It is more likely in such a pool that different source beds have supplied the gas of the different reservoir beds. Of course, if changes in the water pressure of the different reservoirs is active, or if there has been subsequent sealing off of previously connected reservoirs of gas, then the different gas pressures could be possible.

*Distribution of Source Beds, Effect on Lateral Migration.*—The distribution of the source beds must certainly affect the amount and speed of lateral migration. Should there be much source material adjacent to a single reservoir, it is conceivable that lateral migration might progress over long distances and at a relatively high speed. This of course is contingent upon substantial release of pressure toward the migrating point. On the contrary, however, with a paucity of source material adjacent to extensive reservoir beds, it is conceivable that lateral migration over even a short distance might not take place at all. In such a case, there would be ample release of pressure merely within the coarse-pored layers without sidewise movement. However, with a release of pressure along this reservoir bed, very slow lateral migration would no doubt be inaugurated unless the underground water movement was in the opposite direction. In this case it appears that the pool would not be increased by migrated gas.

*Quantities of Gas Generated.*—The quantity of gas generated under a given pressure must affect the amount of lateral migration. Should the source beds give off sufficient gas to fill completely the pore space of the coarse-pored reservoirs then the

tendency to migrate to areas of less pressure will be greater than if some of the pore spaces were occupied by liquids. In the case of complete impregnation by gas particles there would be need of no work to overcome the attraction of the liquid for the pore spaces, and the result might readily be long distance lateral migration of the gas. In this way also the source bed would be free to generate more gas at the same given pressure. If this did happen, conditions of equilibrium in any trap passed, such as an upfold in the coarse-pored beds, become imperative. Differential pressures of any appreciable amount cannot exist and the pool accumulated will be continuous. If differing pressures did occur, the migration would immediately tend to equalize them by flowing to areas of less pressure. Should the gas displace water from some of the pore spaces, similar conditions to those where no water was present are possible, but only if there is sufficient release of pressure elsewhere in the system to inaugurate gas movement. If the pore spaces were so small that the water particles were strongly held by capillary forces, it is conceivable that no movement would occur.

It is apparent that by combining two or more of these points different results may be obtained. The final product, however, must depend on the factor that is most potent. For example, if the gas generated was not sufficent to fill completely the coarse-pored bed and this reservoir had been subjected to differential cementation, one would expect the gas to accumulate in a spotty pool, dependent on the areas of least cementing. Further, if the source beds were in a series of impervious strata that would permit lateral movement and yet were relatively fine-pored, one would expect the gas to accumulate in an area of least pressure but the wells would not yield a great volume, and the pressure would be small. The effect of friction of migrating gas through shales probably influences the yield of wells producing from shale reservoirs. It is a difficult problem to determine whether friction of gas through fine pores plays a more important part than the high capillary forces of such fine-pored rocks.

*Effect of Lateral Migration on the Pool.*—The effect of long distance lateral migration on a pool will be to form a continuous and single pressured gas body. However, should transverse migration be possible in the pool, the secondary pools thus formed must at one time be in equilibrium with the main gas body. If later crustal movement should seal off these secondary pools pressure might then be altered to bring about equilibrium in each pool's particular coarse-pored beds. Should the nature of the reservoir bed change, either by lenticularity or by differential cementation, long distance lateral migration would still tend to form a pool of equal pressure, where the gas accumulated, but the pool would give different yields.

Should long distance lateral migration be effective, the collective area of a favorable structure would play an extremely important rôle in the value of the field, provided the reservoir bed had sufficient pore space to hold all the gas accumulated. Furthermore, if the source beds were thin and capable of yielding small amounts of gas, long distance lateral migration would be very important provided the gas is generated away from the folded area. This last point is often overlooked in petroleum work and yet to the writer it appears to be of major importance.

It has been mentioned above that gas probably generates during all stages in the history of a pool's development. It seems logical, however, that most of the gas is generated during the folding of the beds, because at that time heat and great pressure are acting on the source materials. Hence if the largest volume of gas is formed during the inauguration of the folds, why should we expect this greatest generation to be active in places where the beds are not being folded? Also, if the gas was formed where the strata are not deformed, why should there not be more small gas wells from horizontal beds? It appears probable that horizontal beds do not yield small flows of gas because there is no localization for release of pressure, such as a fold affords, or because a greater generation of gas occurs where rocks are folded.

The collective area could easily be the same size for a small fold as a large one and each should be expected to produce the

same amount of gas, provided each fold had the same amount of source material, the same volume of available reservoir pore space, and had undergone the same amount of deformation. This is not the case in nature where there is a close accord between the size of a fold and the amount of recoverable gas. This connection is certainly suggestive of generation during folding, and only generation in the area being folded. Furthermore it does not require long distance lateral migration in order to accumulate a large volumed field.

### SOURCE BEDS.

In a search for the source beds of the Golden Eagle gas, it is natural to seek a marine formation, since in the origin of petroleum, organic remains of marine strata most generally are considered as the source material. For this reason the Cody shale attracts immediate attention but a careful consideration of the associations of the gas offers proof that the Cody does not fill this rôle.

Had beds of the Cody shale been the source, then traces of either gas or water would have been found in the sandstone strata of the upper part of the formation. Especially would this be expected for the sand correlated with the Shannon sand. Where examined by the writer at its outcrop, about 450 feet below the base of the Mesaverde formation, this sand is made up of angular grains of quartz, feldspar, and hornblende. It is solidly indurated but the pore spaces are visible in a hand lens. The other sandstone beds of the Cody above this sand also appear to be excellent reservoir beds for gas. It is known that these "sands" are lenticular, but the lenses cover such large areas that water under hypdrostatic pressure must be contained in them. Hence for gas to have migrated from beds of Cody shale upward through these sands without having left at least a little gas behind is highly improbable. Likewise that moving water flushed the gas out of these sands without leaving water to appear in the wells that penetrate the sandstones, also seems highly improbable. Yet from the upper Cody sands, the Shannon horizon included, neither water nor gas was encountered. The same objections hold for the mas-

sive sandstone beds of the basal part of the Mesaverde formation, since they also would have been crossed had the upper Cody strata been the source beds of the Golden Eagle gas.

Since the Cody shale, which contains the only possible source beds of marine origin may, therefore, be eliminated,[22] the writer presents the thesis that a non-marine formation was the source of the Golden Eagle gas.

The presence of nearby water-bearing sands, both above and below gas shows, proves that the gas was not driven to its present position by the passage of water through the reservoir beds; the absence of any water below the main reservoir bed of gas shows there could have been no water drive from below. Therefore, the source must have been close stratigraphically to the reservoirs. There remain for consideration as possible source beds only the Mesaverde and the Meeteetse formations, both of continental accumulation.

The Meeteetse is mentioned only because it is the writer's conviction that the shallow shows (around 1,600 feet) represent local generations in the upper part of that formation. But the source of the gas in these small accumulations is in continental strata. It is improbable that the Meeteetse was the main source of all the gas, because downward migration of gas stratigraphically is conceivable only for extremely short distances and because, had the Meeteetse been the main source, a great deal of gas must have remained in the upper sandy division of the older Mesaverde, whereas this zone produced only small amounts. By a process of elimination the possible and most probable source beds are some of the continental Mesaverde strata, and this requires that the gas originated from within the Mesaverde formation.

Since it appears most probable that the source materials were contained in the Mesaverde formation, the next point to be considered is the nature of the organic materials that produced the gas. This is a problem for the organic chemist to determine.

[22] If the Cody be eliminated on the grounds given above it is unnecessary to consider older beds (Frontier formation or Mowry shale) as the same objections hold for them to an even greater degree.

From a geological viewpoint the coals and associated carbonaceous layers appear most likely to have been the beds that yielded the gas. It is known that bituminous coal when heated will release methane, small amounts of ethane, nitrogen and carbon dioxide. A part of these gases is occluded but at moderate temperatures (20° to 100° C.) some of the carbonaceous matter breaks down into hydrocarbon gases.[23] The extreme dryness of the Golden Eagle gas is in accord with such an hypothesis since methane can be and often is formed from decaying vegetation in pools of fresh water. There must have been many such pools during the accumulation of the Mesaverde formation as shown by the coal and the carbonaceous clay beds. Therefore the geological data strongly suggest that the Mesaverde coals were the source of the Golden Eagle gas. As supporting evidence there may be cited the occurrence of gases in coal mines (the fire damp) that approximate the composition of some of the dry gases found in natural gas fields. There is no doubt that these coal mine gases originate from the associated coal. Again, the well logs in which several shows are recorded from sands that lie close to coal layers suggest relationship between gas and coal. Furthermore a study of the outcrops shows coal seams interfingering with the reservoir sandstones.

It is most interesting in this connection to note that lignites with the least fixed carbon content give off more ethane when heated than the bituminous coals, and these in turn more than anthracite that has the highest fixed carbon content. Hence if a natural gas field were found of proven anthracite source, and the gas should contain a large percentage of ethane, there would be very suggestive proof that the gas had been generated while the coal was lignitic.

The possibility that the gas originated from marine strata in the Mesaverde formation that are known to occur to the north of the Golden Eagle field has been considered but rejected. The nearest known marine beds in the Mesaverde crop out in the Oregon Basin quadrangle, 30 miles north of the Golden Eagle

[23] Thom, W. T., Jr., *T. A. I. M. M. E.*, no. 1451F., p. 1. May, 1925.

field. Such a distance, or even half of it, is not in accord with the writer's conception of long-distance lateral migration under even the most ideal of conditions. In this case, it is known further that the present underground water movement in the southern part of the Bighorn Basin is to the north, away from the Golden Eagle area. Although this direction of movement may not have prevailed always, it has been active since the time of the initial development of the Golden Eagle dome. This certainly precludes accumulation of the gas from marine areas of Mesaverde age.

USES.

In 1920 an 8-inch pipe line was built that connected the Golden Eagle field with the city of Thermopolis. The city used about ¾ of a million cubic feet per day for domestic and industrial purposes and was made more livable by its acquirement of this fuel.

The manufacture of carbon black also supplies a use for natural gas, but in 1919 the Wyoming legislature prohibited the use of gas for the manufacture of carbon black in any field situated within nine miles of an incorporated town. Because of this law several plants in the State were closed but one plant was moved from Lovell in the northern part of the Bighorn Basin, where gas from the Garland Anticline had been used, to the Golden Eagle field. The capacity of this plant is 60 barrels which means it used approximately 2½ million cubic feet of gas per day. Owing to poor carbon black markets, the plant operated only from the summer of 1920 until the fall of 1924. The gas is poorly adapted to the manufacture of carbon black and the investment must have been a great loss. The heavy drain of the plant on the field was not manifest until 1925 at which time there was not sufficient gas to supply the town. This could have been anticipated if the reservoir and source beds had been considered. Any law regulating the use of natural gas for manufacturing carbon black should never allow gas to be used from fields like the Golden Eagle, regardless of their distance from towns. Gas fields of this nature that have extremely thick and porous reservoir beds

but only small areal extent must always give relatively large initial yields, of short duration, and hence are not adapted to continuous large yields. It is to be regretted that the law prohibits use of gas for carbon black manufacture from potentially enormous fields and allows it from fields like the Golden Eagle, merely because of geographical position with no regard for the scientific interpretation of the geologic controls.

The gas, as mentioned above (see above NATURAL GAS, *Kinds*), is not adapted to manufacture of casinghead gasoline. The absence of gasoline in the gas is well demonstrated by the analyses in which there is no ethane; in ordinary gas analyses all the hydrocarbon compounds heavier than methane are shown as ethane and hence any gasoline content may be determined from the ethane of the analyses.

CONCLUSIONS.

The geological study of the Golden Eagle field strongly suggests that the source materials are contained in continental beds in the Mesaverde formation of Montana age. The reservoir beds are part of the same formation. The exact organic source of this gas is a problem for an organic chemist, but the geological associations and the chemical analysis of the gas leave little doubt that coal or other carbonaceous layers, closely associated with the reservoir beds, contained the source matter. Whether the gas was generated prior to consolidation, during consolidation, or at the later folding of the strata cannot be ascertained definitely. It appears probable that generation in the Golden Eagle field occurred during all three periods.

Lateral migration and accumulation from distant marine beds seem impossible and hence the writer believes marine Mesaverde beds that crop out 30 miles to the north of the field did not supply the gas produced.

Local generation of small amounts of gas from associated coaly substances is the most probable explanation of shows of gas found in the upper part of the Meeteetse formation. It is also highly probable that many other shows recorded in the well logs were derived from local generations of gas, from closely associated coal layers.

The potential flow of the field was 25½ million cubic feet per day but in 1925 it had fallen off to less than ¾ of one million cubic feet. Such a condition is to be expected from thick porous reservoirs and a small area within the structural closure.

The gas should have been conserved for the domestic needs of the city of Thermopolis since it is not suited to the manufacture of carbon black, or the extraction of gasoline, and the geological conditions of the field indicated a short life.

These data and the conclusions arising therefrom offer a new line for further investigation in the matter of the origin of natural gas in general. They certainly establish an important new fact in regard to this particular area, the Golden Eagle field.

YALE UNIVERSITY,
NEW HAVEN, CONN.

# THE MINERALS OF THE INTERMEDIATE ZONE. BUTTE, MONTANA.

WILLIAM M. AGAR.

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THIS paper presents the results of a microscopic study, preceded by field investigation, of a suite of two hundred and fifty specimens collected in the mines of Butte, Montana, partly by the writer while in the employ of the Anaconda Copper Mining Company and partly by Mr. C. H. Steele, of the Geological Department of that company.

The writer wishes to thank Mr. R. H. Sales of the Anaconda Copper Company for the opportunity to do this work and particularly for his permission to publish the results. He is also greatly indebted to Professor Alan M. Bateman of Yale University for reading and criticizing the manuscript as well as for the loan of several specimens containing enargite from the stopes above the 2200 ft. and 2400 ft. levels of the Badger-State vein.

The ores of Butte have been studied microscopically many times since the publication of Sales'[1] classic paper, but much of this work has dealt with the problem of the origin of the chalcocite or has been restricted to the central part of the camp, the "copper dome" rich in chalcocite and enargite.

The specimens upon which this report is based were collected from the northern and western parts of the district well out in the intermediate zone. The study was undertaken in the hope that

[1] Sales, R. H., "Ore Deposits of Butte, Montana," *T. A. I. M. M. E.*, vol. XLVI., 1913, pp. 59–60.

some knowledge of the relations of the sphalerite to the copper sulphides might be gained that would be of value in future development work. Up to the present time this hope has not materialized but the study is believed to throw some new light upon the complicated interrelations of the sulphide minerals. It adds little to the excellent argument for the hypogene origin of the deep seated chalcocite from microscopic evidence which has been presented by Locke, Hall and Short [2] but, by leading to the same conclusions, it cannot but strengthen the argument.

## THE INTERMEDIATE ZONE.

The presence of three zones of mineralization in the Butte deposits forming concentric shells with fairly definite boundaries was first recognized by Sales.[3] The ores of the central zone are marked by the predominance of chalcocite and enargite in a gangue of quartz and pyrite; bornite is present in smaller amounts, covellite is uncommon and sphalerite and chalcopyrite are rare.

The intermediate zone contains little enargite but proportionally greater amounts of bornite, chalcopyrite, tennantite, and tetrahedrite. Chalcocite remains about the same but sphalerite becomes an important constituent and galena, covellite, rhodonite, and rhodochrosite occur in variable quantities. This mineralogical change is accompanied by a decrease in copper content and an increase in the amount of zinc, lead, manganese, and silver. The boundaries between the two are naturally nowhere sharply defined and the change outlined above becomes progressively more marked outward and upward from the central area.

## THE VEINS STUDIED.

The State vein is an east-west vein, near the northern limit of the intermediate zone and is one of the large producers of copper and zinc in the Badger Mine. Specimens were collected from the

[2] Augustus Locke, D. A. Hall, M. N. Short, "Rôle of Secondary Enrichment in Genesis of Butte Chalcocite," *T. A. I. M. M. E.*, vol LXX., pp. 933–963.

[3] *Loc. cit.*

1,100-foot drift down to the 2,000-foot drift and were as evenly spaced throughout that area as the mine workings would permit.

The Original No. 2 Vein is a split from an east-west vein (the main Original Vein) and has been a large producer in the Original, Stewart, and Colorado mines. The specimens were collected from the 1,700-foot drift down to the 3,400-foot level.

These two veins show remarkably little difference in the microstructures of their ores. The same general paragenesis obtains for both and the same variations occur. Enargite is present in greater quantities throughout the No. 2 Vein than in the State Vein but it increases in quantity in the latter in the stopes below the 2,000-ft. level. This is the only case of a progressive change in mineralization from top to bottom noted in either vein. The most marked difference between the two veins is the fact, as noted by Mr. C. H. Steele, that there is a tendency for sphalerite to occur on the foot wall and the copper sulphides on the hanging wall of the State Vein. This is not true in the original No. 2 Vein. The specimens collected amply uphold this fact but the microscope does not afford an explanation. Because of this identity of mineral content and similarity of the relations between the minerals of the two veins they are described together.

Quartz, pyrite, and sphalerite form the bulk of the filling in both veins with the latter fluctuating most in quantity. It is sometimes nearly absent, it is usually subordinate to pyrite, and occasionally it displaces pyrite completely from a restricted area. Chalcocite, bornite, tennantite, chalcopyrite, galena, and covellite, in their order of abundance, fill in cracks in the first-named minerals or replace the pyrite and sphalerite. They show more or less complicated relations with one another.

### THE CHARACTERISTIC MICROSTRUCTURES.

Locke, Hall, and Short [4] pointed out that the microstructures found in the one thousand specimens examined by them were limited to about one dozen principal varieties. They base the soundness of the microscopic argument upon the fact that the

[4] *Loc. cit.*, p. 951.

same relations are repeated over and over so that the relatively small areas examined give a fair average of the whole. Once more this study serves to confirm their conclusions. A greater number of minerals occur frequently in the intermediate zone than in the central zone, but the microstructures are relatively few and these few recur continually.

Those types characteristic of undoubted supergene replacement [5] are missing. This is as should be expected from the fact that the 1,100-foot level of the State Vein was the highest level sampled. Type three of Locke, Hall and Short, the lattice of chalcocite and bornite independent of visible channels, is occasionally present. Type four, the intimate and uniform mixing of the two which appears under low magnification as bornite off color, is rather common. Type five, the mutual boundary relation, is the commonest relation between these two as well as between many of the other minerals.

The mutual boundary relations frequently grade in parts of the same microscopic field into apparant replacement relations. That is, one mineral will project into the other in the form of fine lines. These little veins are not controlled by any obvious channels but are apparently younger than the minerals that they cut.

The graphic and mutual boundary textures are frequently found in the same microscopic field.

The suggestion made by Locke, Hall and Short,[6] that the graphic texture is characteristic of both the central and the intermediate zones while the lattice is characteristic of the central zone only is borne out in this study. The lattice texture is rarely seen in these specimens but the graphic texture is a rather common type.

## THE RELATIONS BETWEEN THE MINERALS.

Quartz, pyrite, and sphalerite, or any one, or any two, form the major part of nearly every microscopic mount. When two or more are present they are intercrystallized in a manner similar to that of the minerals of an igneous rock and are undoubtedly

[5] *Op. cit.*, p. 954.
[6] *Op. cit.*, p. 956, footnote.

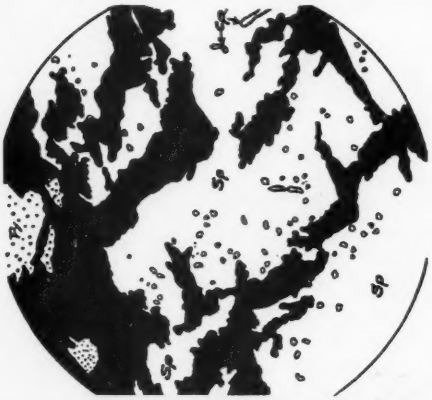

FIG. 1. Chalcopyrite occurring as dots and rods in sphalerite. Dotted areas are pyrite. White areas are sphalerite. Black areas are holes in the specimen. Dots and rods of chalcopyrite (*Cp*). Camera lucida drawing. × 50.

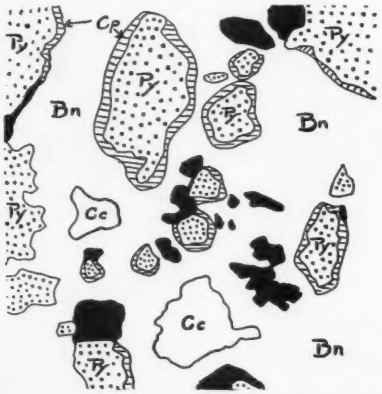


FIG. 2. Chalcopyrite forming rims around pyrite and in turn surrounded by bornite which gives way to irregular areas of chalcocite. Dotted areas are pyrite (*Py*); lined, chalcopyrite (*Cp*); white, bornite (*Bn*), with two areas of chalcocite (*Cc*). Black areas are holes in the specimen. Camera lucida drawing. × 135.

contemporaneous. A minor amount of sphalerite forms fine lines projecting into pyrite in a manner suggesting replacement. This sphalerite is frequently continuous with an area showing contemporaneous relations with pyrite and does not appear to be a second generation but results rather from the continuation of its period of deposition somewhat longer than that of the pyrite.

A small amount of galena is present as irregular lobes and patches in sphalerite and belongs with the first period of mineralization. Tennantite [7] occurs in considerable quantities and nearly always replaces sphalerite though it may replace bornite or show the mutual boundary relations with it.

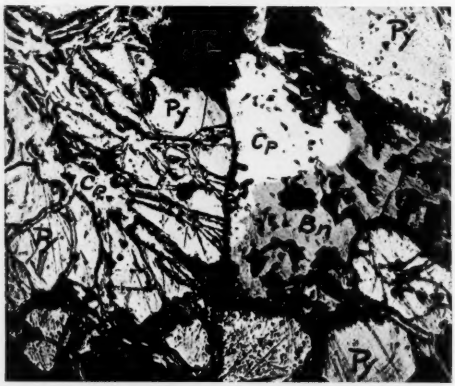


FIG. 3. Chalcopyrite (*Cp*) replacing pyrite (*Py*) and bornite (*Bn*). Reflected light. × 160.

Chalcopyrite exhibits the most varied relations of all the minerals. It may occur as dots in sphalerite (Fig. 1) or as rims around pyrite (Fig. 2). It may clearly replace pyrite (Fig. 3), sphalerite, tennantite, or bornite (Fig. 4), or it may show mutual boundary relations with bornite. It is never seen replacing chal-

[7] This probably always contains some tetrahedrite. They are indistinguishable under the microscope and are here listed together as tennantite.

cocite nor is it present in any great quantities when that mineral is present. Chalcopyrite is never an important ore but few microscopic mounts are entirely free from it.

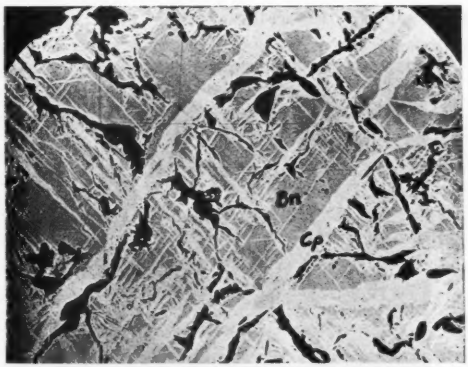


FIG. 4. Chalcopyrite (*Cp*) replacing bornite (*Bn*) without any visible relation to fractures. Reflected light. ×60.

Bornite is found replacing pyrite or sometimes sphalerite, as intergrowths with tennantite, or more commonly, intergrown with chalcocite in a number of different ways. Few areas of bornite are entirely free from chalcocite and no considerable area of chalcocite is free from bornite. The relations between the two are usually those of the mutual boundary or graphic textures (Fig. 5) but these frequently grade into replacement relations. Chalcocite is generally the later of the two but bornite may infrequently fill that rôle.

Chalcocite may also replace tennantite. In some areas chalcocite and tennantite are so intimately mixed that they can barely be resolved with a high power objective. It is not known whether this represents replacement or an intergrowth.

Galena may be contemporaneous with sphalerite as noted before. In other cases it clearly replaces sphalerite. These are believed to represent two distinct generations of galena since the

first shows mutual boundary relations with sphalerite and the second may show the same relation to bornite as well as replace sphalerite.

Covellite is rarely seen in these ores and then only in minute quantities. It appears to be of the same age as the bornite.

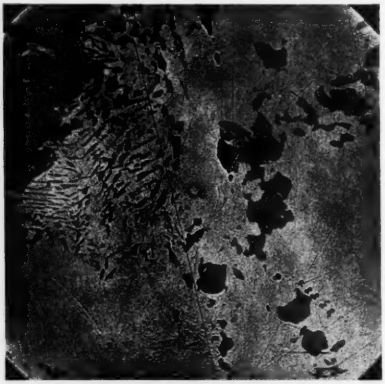

FIG. 5. Chalcocite (*Cc*) and bornite (*Bn*) showing graphic and mutual boundary textures. Reflected light. × 50.

The position of enargite cannot be fixed with certainty in this series. Throughout the greater part of the two veins it is only sparingly present as irregular, rounded grains completely surrounded by sulphides of copper and its relation to the other minerals cannot be determined. In a few specimens from the stopes between the 2,000-foot and the 2,400-foot levels of the State Vein it forms the major part of the ore and includes rounded grains of pyrite and shreds of sphalerite. It is in turn partly replaced by an intergrowth of bornite and chalcocite or by chalcopyrite. The chalcopyrite commonly attacks the remnants of the sphalerite or the bornite but may replace enargite directly. One specimen shows rims of tennantite encircling worn and rounded enargite in a field of chalcocite and bornite.

This evidence, though scanty, points to a position for enargite in the sequence of the minerals of the intermediate zone similar to that ascribed to it in the sequence of the central zone by Locke, Hall, and Short.[8] Enargite is therefore tentatively placed after pyrite and sphalerite but before the other sulphides of copper.

Rhodonite, rhodochrosite, and calcite are sometimes present and clearly belong to the generation of the copper sulphides.

### THE MEANING OF THESE RELATIONS. PARAGENESIS.

The relations described above are fairly complex and do not point to any clear-cut time differences between the copper sulphides. The three minerals pyrite, quartz, and sphalerite however never replace any of the copper sulphides and clearly were formed first. Sphalerite may have continued to form for some time after pyrite but never lagged far enough behind to lap over onto the copper mineralization. A "halo of zinc ore richer than the average with two generations of sphalerite" has been recognized as "fringing the copper shoots in the east-west veins."[9] Mr. M. H. Gidel of the geological department of the Anaconda Mining Company long ago suggested that this was due to sphalerite driven out from lower regions by the later copper-bearing solutions and reprecipitated in cooler regions along the edges of the copper zone. The results of such an action should be visible under the microscope as sphalerite with two distinct relations to the minerals that surround it. This is not so, however, and with the exception of the small quantity of sphalerite which suggests a replacement of pyrite the two are contemporaneous.

Subsequent to the formation of the quartz, pyrite, and sphalerite, the copper sulphides were introduced. No estimate can be made of the time which elapsed between the two. The evidence of every microscopic field points to a time interval but only two specimens showed any brecciation.

The first thing that becomes apparent upon examining these

[8] Augustus Locke, D. A. Hall, M. N. Short, "Rôle of Secondary Enrichment in the Genesis of Butte Chalcocite," *T. A. I. M. M. E.*, vol. LXX., 1924, p. 958.

[9] Billingsley, P. and Grimes, J. A., "Ore Deposits of the Boulder Batholith of Montana," *Bull. A. I. M. E.*, April, 1917, p. 675.

copper sulphides is that no clear distinction in age can be drawn between them. There is a general tendency to replace the older iron and zinc sulphide by copper sulphide but there are many missteps and frequent partial reversals of the reaction. Fig. 2, showing pyrite surrounded by chalcopyrite and this by bornite which in turn gives way to chalcocite, is a clear-cut example of the substitution of copper for iron. It is an unusual case, however, and pyrite frequently gives way to bornite only to suffer a return to higher iron and lower copper when bornite is replaced by chalcopyrite.

According to J. C. Ray [10] bornite and chalcopyrite in the "covellite zone" are formed by the influence of pyrite which is resorbed by chalcocite while in the colloidal state. Chalcopyrite is said to be generally due directly to the replacement of enargite, and bornite to the replacement of covellite. If Fig. 2 were a typical sample, the formation of chalcopyrite and bornite would appear to be controlled by the presence of pyrite. In reality, however, such textures are rare and though chalcopyrite and bornite frequently do replace pyrite they may also replace sphalerite or tennantite without any apparent relation to pyrite. Doubtless some of the iron that entered into the composition of these minerals was derived from the destruction of pyrite but it did not reenter into combination immediately. The elements replaced are usually carried away, witness the disappearance of zinc where sphalerite is replaced; it is only in rare instances that rims such as are featured in Fig. 2 are to be seen. According to this, a local blocking of the freedom of circulation of the solutions would be necessary to account for the formation of these rims and to show the stages in the process.

### THE MICROSCOPIC RELATION OF CHALCOPYRITE.

In the first case noted under characteristic microstructures, namely chalcopyrite as dots in sphalerite, the dots may be irregular or elongated into the form of rods. Only a few of the many occurrences of this texture show the rod-like form but enough

[10] Ray, J. C., "Paragenesis of the Ore Minerals in the Butte District, Montana," ECON. GEOL., vol. IX., No. 5, p. 481.

of them are elongated to suggest that many are rods cut at various angles. The significance of these forms is doubtful. They cannot well show replacements but are believed to be contemporaneous growths or, as Schneiderhöhn [11] suggests, unmixing from solid solution. Schneiderhöhn's figures show many more of the rod-like forms than are present in the Butte ores but otherwise the two are identical. If this be the correct interpretation then the chalcopyrite must be of the same age as the sphalerite. Veinlets of chalcopyrite cutting sphalerite are frequently seen in the Butte ores adjacent to an area showing these dots. These same veinlets may cut bornite and tennantite as well as sphalerite and pyrite and belong therefore to a later period of mineralization.

The second type, rims of chalcopyrite around pyrite, shows one step in the replacement of pure iron sulphide by pure copper sulphide. The pyrite is surrounded by a thin halo of chalcopyrite and this by bornite. The boundary between the chalcopyrite and bornite is frequently feathery and the bornite passes irregularly into bluish chalcocite near the centers of its areas. This, in turn, may be cut by fine lines of white chalcocite.

The third type, chaycopyrite replacing any one of the other minerals excepting chalcocite, is characterized by branching veins of chalcopyrite cutting through or following the borders of other minerals. Very rarely a lattice texture is developed.

Chalcopyrite that shows mutual boundary relations with bornite is rare. When these two are found together they are usually seen to be replacing sphalerite or pyrite.

The frequent occurrence of tennantite is a step outside of this general tendency to substitute pure copper for pure iron sulphide. Tennantite has no clearly fixed place among the copper minerals but is usually an early one that results from the introduction of arsenic. It has been suggested that some of this arsenic may be due to the breakdown of enargite in the central zone and the reprecipitation of the arsenic in smaller quantities further out.[12]

[11] H. Schneiderhöhn, "Anleitung zur Microkopischen Bestimmung und Untersuchung von Erzen und Aufbereitungsprodukten besonders im Auffallenden Licht," *Selbstverlag der Gesellschaft Deutcher Metallhütten und Bergleute e. V. Berlin*, 1922, p. 164 and figures.

[12] Sales, R. H., verbal communication.

This suggestion arises from the fact that tennantite is frequently seen as a crust of fine, shiny crystals coating the other minerals. The microscope shows it only as one of the minerals of the second period, which is in accord with that idea, but gives no clue from whence it comes.

No local changes in the wall rock or in the depth or amount of its alteration can be called upon, so far as known, to explain the minor variations in the relations of the minerals. According to Sales [13] the ore types and the conditions of alteration are related in a general way but this refers to the presence of the greatest wall rock alteration in the central copper zone and less though considerable alteration in most of the intermediate zone. It does not refer to any continuous minor variations accompanying the vagaries of the sulphide relations.

To sum up, many of these sulphides show mutual boundary and graphic relations; one may appear to be older in one specimen and younger in the next. Many of the microstructures are indefinite. Clear replacement along visible cracks, so characteristic of supergene conditions, is lacking and replacement is local and subject to reversal. Chalcocite cannot be considered as distinct from the other minerals. It is often the last to form but is generally contemporaneous with bornite. These relations do not point to successive periods of mineralization, either hypogene or supergene, but appear rather to result from continuous deposition in a more or less regular series, subject to control by local variations in the composition of the solutions as well as by a general increase in their copper content. Reactions with the already existing minerals and blocking of the freedom of the circulation of the solutions probably account for the anomalies.

The copper sulphides are believed to belong to one period of deposition and to form a series younger than pyrite and sphalerite.

The following table gives the paragenesis of these sulphides in graphic form:

[13] Sales, R. H., "Ore Deposits of Butte, Montana," *T. A. I. M. M. E.*, vol. XLVI., p. 3–106.

| I. | | II. | |
|---|---|---|---|
| *A.* | *B.* | *A.* | *B.* |
| Pyrite | Sphalerite | Tennantite | Chalcopyrite |
| Sphalerite | Enargite | Galena | Chalcocite |
| Minor { Galena | | Bornite | |
| Minor { Chalcopyrite | | Chalcopyrite | |
| | | Covellite | |
| | | Chalcocite | |

SUMMARY.

This report deals only with the minerals of the intermediate zone. The veins studied are the Badger State, an east-west vein in the northern part of the intermediate zone; and the Original No. 2, a split off an east-west vein in the western part of the same zone.

The minerals present in this zone are quartz, pyrite, sphalerite, galena, chalcopyrite, tennantite, covellite, bornite, chalcocite, and some enargite, calcite, rhodochrosite, and rhodonite.

The relations between these minerals are complex but the microstructures are few in number. They are mostly mutual boundary, graphic, and replacement textures not of the typically supergene types.

Pyrite, quartz, and sphalerite form one generation of minerals. These are replaced by the intricately intergrown copper sulphides.

The intricate relations among the copper sulphides point to continuous deposition under somewhat variable conditions. They are essentially contemporaneous.

YALE UNIVERSITY,
NEW HAVEN, CONN.

# EDITORIAL

## *THE INTERNATIONAL GEOLOGICAL CONGRESSES.*[1]

The suggestion or plan of an International Congress of Geologists was first formulated at a meeting of the American Association for the Advancement of Science, held in connection with the Centennial Exposition, Philadelphia, in 1876. A committee was appointed and correspondence ensued with geologists abroad, who manifested such interest in the plan that the first Congress was held in Paris in 1879. French, the language of diplomacy, was chosen as the official language of the Congress, but experience has since shown the necessity of permitting authors to write, speak, and print in English, German, Spanish and Italian as well. With all these languages available, almost every geologist the world over has a means of communicating his results to his colleagues. Triennial sessions were decided upon at the first congress, and naturally the meetings were to be held in succession in the various countries where geology flourishes. The second Congress was held in 1882 in Bologna, Italy, and since then have followed those of Berlin, 1885; London, 1888; Washington, 1891; St. Petersburg, 1894; Geneva, 1897; Paris, a second time in connection with the great exposition of 1900; Vienna, 1903; Mexico, 1906; Stockholm, 1910; Montreal and Toronto jointly, 1913; Brussels, 1922, and Madrid, 1926.

In the earlier congresses, excursions to points of interest with the carefully prepared and elaborate guide-books of later years, were lacking, but with the fifth Congress, at Washington, and a long trip across the continent in prospect, a guide-book became essential. The U. S. Geological Survey, therefore, prepared one which not only met the needs of the congress, but was also the precursor of the present day indispensable guide-books which we

[1] Written before the XIV International Geologic Congress held in Madrid, 1926.

owe to the Survey and which cover the chief transcontinental lines. The custom was continued at the St. Petersburg Congress, with its no less extensive excursions, and has remained in full force ever since. Not the least valuable of the contributions from the several congresses have been these guide-books, prepared as they are by specialists and relating to the most interesting features of the countries where the sessions are held.

At the very early congresses, Paris or Bologna, the project of a geological map of Europe was adopted, the scale was selected, and the several local sections were assigned. But then arose the questions of colors and of the standard time divisions and their names. Committees were appointed at Bologna, 1882, to report on these matters at Berlin, 1885, and as a result we have the important recommendations which are in the proceedings. This Third Congress decided on a double time and formational scale; viz., for the former in decreasing order, Era, Period, Epoch, Age, and for the latter, Group, System, Series, Stage. The use of Age for the smallest time division met with much criticism and opposition in America, especially from Professor James D. Dana who had been accustomed, as had others, to speak of the Age of Invertebrates, the Age of Fishes, the Age of Reptiles, etc., as large time divisions. Despite, therefore, the great desirability of uniform and intelligible usage in these matters, the time scale never received universal approval, although in all but the term Age it is now well nigh the standard of all nations cultivating geology. The physical terms are more loosely employed, but System, Series, and Stage are almost universal in the order suggested by the Berlin Congress.

A trial of the selected colors for the periods was made on a geological map of the United States, which was prepared by Professor C. H. Hitchcock and published by the American Institute of Mining Engineers, two or three years after the Third Congress adjourned. The map was a very useful one and was widely circulated, but it is, of course, now out of date, especially in the Pre-Cambrian in which, as then mapped, were many intrusive granites now known to be later. The map also showed that the

variations of brown selected respectively for the Cambrian and Devonian were too much alike, so that in this particular, improvement was possible. The ensuing experience was fruitful and played its part in the movement in the U. S. Geological Survey to establish a standard series of colors for its rapidly increasing maps and folios. We have, therefore, the valuable report in the Tenth Annual of the Survey with its plates of colors, its plan of patterns of slightly deeper tint laid on a flat base color, and its suggested conventions in black on white, for photo-engraving. The colors were chosen in excellent taste and marked a great advance over many shrieking incongruities of earlier maps.

The Washington Congress prompted also one other movement of more than ordinary interest, which was the preparation of the Correlation Bulletins of the Survey. Unfortunately various difficulties prevented the completion of as many as could have been wished, and only the one on the Devonian was placed in the hands of the delegates; but it was shortly followed by the one on the Cambrian and in the course of years by the entire series. The subject of "Correlation" became a very live one, and found an interested and sympathetic audience in the subsequent congresses.

At the St. Petersburg Congress, the subject of the classification of igneous rocks was brought up and excited much interest, as did also the proposal to establish an international journal of petrology; but neither discussion led to any great or decisive unanimity. At the Geneva Congress, both the phenomena of mountain making, as exhibited to the delegates in excursions among the Alps, under the guidance of the veteran Albrecht Heim, and the underlying conceptions of deep-seated flowage came to the fore and exercised their influence in much subsequent investigation. At the congress in Mexico, ore deposits figured naturally in a prominent way, and in the Comptes Rendus, the student of this branch will not fail to find important papers.

But it was the Eleventh Congress in Stockholm that blazed a trail into a new and extremely important field and one which is yearly becoming of greater and greater international moment. It opened up the region which lies between mining geology and

economics. Since Sweden is one of the principal sources of iron ores and a notable center of the iron and steel industry, the subject of the "Iron Ore Reserves of the World" was chosen for a great, coöperative report on the estimated resources in these ores of all the countries of the world possessing them. A vast amount of useful information was brought together, and while the individual reports are of somewhat unequal merit—Hungary, for example, not a very important factor in the iron industry, having the longest and most detailed report of all—the volume is one of the most notable economic contributions of our time.

Iron reserves having been treated, the natural subject for the Canadian Congress, which followed in 1913, was Coal; consequently, we have the great work on this indispensable source of power, as a sound basis of much economic reasoning. Since the issue of these two reports, the subject of the supplies of raw materials for fundamental industries in all the great industrial nations has come more and more into the foreground. The work of the War Minerals Committee in the United States, and the publications emanating from its members since the Armistice, the Williamstown Conference of last summer,[2] and the one in prospect for next summer,[3] are all symptoms of incubating ideas of great portent for the future.

The Madrid Congress of 1926 continues the discussions by taking up the phosphates and pyrites, two fundamental and interwoven industries.

Many other subjects of exceptional interest have been discussed by the congresses and are duly recorded in the Comptes Rendus; but quite as important as any of the results are the opportunities to form international friendships and to meet face to face with colleagues interested in the same branches of geology though situated at opposite ends of the earth's diameters. The hospitality of Spain makes possible this year visits to regions of copper mining and of silver-lead production which go back beyond the dawn of history and which will be viewed by delegates from the New World with respect and interest impossible to express adequately in words.

JAMES F. KEMP.

[2] 1925. [3] 1926.

# DISCUSSION
AND
# INFORMAL COMMUNICATIONS

## *RELATIONS BETWEEN SOLUBILITY AND PRESSURE.*

*Sir:* Dr. A. C. Spencer in his criticism of my treatment of the above subject in "A Discussion on Metasomatism and the Linear Force of Growing Crystals" has merely deduced a special case, previously recognized, from my general one. In simplifying my equation he entirely ignored the definition of the activity of a salt and as a result of this his equations are absolutely incorrect, though they have the same form as the correct thermodynamic one and can be used for empirical interpolation purposes. More explicitly, Dr. Spencer's equations, which he presents as applying to perfect solutions generally, apply only to perfect solutions of the unionized type such as that of sugar in water. His equations are thus quantitatively wholly inapplicable to solutions of salts which ionize in solution.

In other words, Dr. Spencer, in making the assumption that salts form perfect non-ionized solutions, tacitly assumes that the activity, $a_2$, of salts is equal to the product of the activity coefficient, $\gamma$, and the mol fraction $N_2$. By making this incorrect assumption his equation is in error by a factor of two.

A much better way of making Dr. Spencer's simplification is to assume the activity coefficient, $\gamma$, to be constant in the saturated solution and the resulting equation becomes

$$\frac{d\,ln\,N_2}{dp} = \frac{RT}{2(V_1 - \bar{V}_2)}$$

in contrast with Dr. Spencer's equation

$$\frac{d\,ln\,N_2}{dp} = \frac{RT}{(V_1 - \bar{V}_2)}.$$

I am sorry that the results Dr. Spencer arrived at should have cost him "considerable tribulation" but, considering that my conclusions were quite general, he would hardly seem justified in describing my mathematical expressions as "cumbersome" or in stating that he derived his equation "by completing the analysis begun by Dr. Boydell."

The general case is usually accepted as implicitly containing a special one, more particularly when, as in this instance, the special case is obvious and one which, further, had been previously treated by Lewis and Randall ("Thermodynamics," 1923, p. 228). Dr. Spencer is quite incorrect in his statement, ". . . it appears that on the way from definition to differentiation Mr. Boydell has transposed his two cases. As the treatment on page 17 of his discussion is that appropriate for uniform pressure and that on page 21 applies to Case I. and not to Case II. (as these are defined on page 15) the conclusions arrived at by Mr. Boydell are seen to be improperly founded."

Under Case I., I dealt with pressure-solubility relations where "The solid phase and the solution are under the same pressure for a sufficient time to permit equilibrium to be established (*i.e.*, for the solution to become saturated with the solid)." Case II. treated the same relations where "The solid and solution are at no time under the same pressure." My mathematical treatment and the conclusions I arrived at are consistent with those conditions. Dr. Spencer's misapprehension to the contrary is due to his having overlooked the fact that thermodynamics, taking no cognizance, as it never does, of mechanism, is not concerned with whether pressure is due to thrust or shear or not. In Case I. pressure is thermodynamically uniform for sufficient time to allow equilibrium to be established and in Case II. that condition does not hold.

In connection with Dr. Spencer's reference to Williamson's work I can only repeat what I wrote in my paper, viz., "Williamson has dealt with the effect of strain on heterogeneous equilibrium in a thorough and satisfactory manner. His mathematical treatment of the subject, following Gibbs, is more general and in-

volved than the one that follows and lacks application to geological conditions, but his conclusions are substantially in agreement with those following." That still remains my considered opinion and it would seem to me that just as Dr. Spencer has quite misunderstood my treatment of solubility-pressure relations, so he has failed to grasp the essentials of Williamson's broader handling of the same subject. He certainly has not grasped the significance of Williamson's own admission (p. 283) of the possible influence of Becker and Day's experiments on his (Williamson's) own conclusions.

With reference to the criticism of Dr. Lovering it would seem to me that he has hardly made allowance for the limitations in explanation that are imposed on any writer who contributes a paper of some sixty pages to a technical journal.

The assumption of isothermal conditions in metasomatism that Dr. Lovering complains of I intentionally left to the reader to form his own opinion on. Since the rate of reaction in metasomatism depends on the rate of ingress of the reacting solution, since ingress is *through* the already deposited metasome and *rate* of ingress to "the front" must consequently be slow, I assume that the reactions of metasomatism proceed slowly too.

The transportation of material in solution to and from the site of metasomatism, to which Dr. Lovering refers, has already been dealt with by me at length [1] so that repetition of the treatment is unnecessary here. I regret that the reference to Taber's paper "Mechanics of Vein Formation" was given incorrectly and thank Dr. Lovering for the correction. Dr. A. C. Lane has kindly drawn my attention to the fact that Ransome's paper (referred to on p. 42 of my article) is in U. S. Geological Survey Bulletin 182 instead of 180 as stated by me. The objections against the theory of vein formation by crystal growth were not evaluated quantitatively by me in their summation because that had already been done in dealing with each objection *individually*.

Dr. Lovering's discussion of my mathematical treatment being based on Dr. Spencer's criticism which I have already shown to be

[1] *Bulletin Institution of Mining and Metallurgy* (London), Dec., 1924, p. 83.

fallacious need only be mentioned and dismissed, but one of Dr. Lovering's statements " . . . Furthermore, thermodynamic laws only apply rigorously to perfect solutions . . ." is palpably incorrect and requires to be corrected instantly as being extremely misleading. By introduction of the *activity* concept G. N. Lewis extended the application of thermodynamic treatment to solutions generally. It was neglect of this fact that caused Dr. A. C. Spencer to deduce mathematical relations, *applicable to ideal solutions only,* under the misapprehension that he was dealing with solutions generally. The reason why I did not mention the paper by Taber in which he refers to his experimental work was that after reading it I considered the experiments so utterly insufficient to justify the conclusions drawn from them as to the influence of linear " force of growing crystals " in vein formation that I did not consider it worth referring to. At the present time there is probably no branch of science other than geology in which it would be possible to draw, from experimental work carried out in thin glass or porcelain vessels under small pressures, conclusions as to the lifting of thousands of feet of superincumbent rock or the exertion of forces comparable to those " involved in mountain building movements," by the linear " force of growing crystals " without exposing oneself to ridicule. To such a pass has unrestrained speculation and extrapolation beyond the facts brought economic geology!

With regard to the difficulty attending transference in metasomatism of material in colloidal solution I clearly stated (p. 30) " . . . the ability of colloidal particles to be transported in this way will evidently depend on the ratio of their diameter to the width of the openings through which flowage takes place " and left the reader to draw his own conclusions as to where colloidal solutions could be effective. Evidently, in this connection, the degree of dispersion, *i.e.,* the size of the dispersed particles (which is variable even for the same substance) must be taken into consideration.

If Dr. Lovering gained the impression " that the reactions of metasomatism take place in minute openings through the action of

colloidal solutions in process of transport" to the exclusion of molecular (true) solutions, then he is forgetful of what I have clearly written in another place[2] and with which he should be familiar. There I, as the writer, stated distinctly my wish ". . . to avoid giving the impression that he advocates accepting the colloidal condition of matter as explaining the formation of all mineral deposits or, indeed, as being the only factor involved in any one particular occurrence. He fully recognizes that such is far from being the case, that other explanations are possible and that many other factors may be involved. In presenting the foregoing he desires to pose neither as a Daniel come to judgment, a personification of the proverbial new broom, nor does he, Aladdin-like, cry 'New lamps for old.' The writer merely urges that as the good workman carries in his working kit tools suitable for all phases of his work, the geologist and mining engineer should bring to bear on their problems all possible scientific aids, and he submits that the influence of colloidal solutions is certainly one of these."

Touching the criticism of both Dr. Spencer and Dr. Lovering, I have to complain that both of them deal only with details and leave entirely untouched the main question at issue. The portion of my paper that the criticism of each refers to is that in which I attempted to show the inadequacy of the so-called linear "force of growing crystals" in vein formation to produce the effects claimed for it. Neither of my critics touch this important phase, which if substantiated by facts imposes a distinct limitation on replacement. I would ask them in all courtesy if such criticism does not tend to add to our *conversation* rather than to increase our *knowledge?*

Referring to Dr. Spencer's separate criticism under caption "The Alteration of Plagioclase to Sericite" in which he states that "the process detailed by Mr. Boydell would result in the formation of an extremely porous metasome aggregate quite different from the fairly compact aggregate which the imagined process seeks to explain." To this I reply that the process would give rise, at one stage, to a substance with high porosity, the pores of

[2] *Op. cit.*, p. 104.

which would be submicroscopic as are those of silica gel for example. The change silica gel → opal → chalcedony is well established yet the chalcedony of gel origin gives no evidence microscopically of being "an extremely porous" substance such as Dr. Spencer would seem to think all colloform substances necessarily are.

His suggestion that my ideas on gel metasomatism in connection with the formation of sericite could be checked by experimental determination of the porosity of secondary sericite assumes, inter alia, that porosity of the sericite is necessarily permanent, a condition that, according to my ideas, by no means holds.

H. C. BOYDELL.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY,
CAMBRIDGE, MASS.

## *METASOMATISM AND THE PRESSURE OF GROWING CRYSTALS.*

*Sir:* Metasomatism has been defined in somewhat different ways by different writers. For the purposes of this paper it may be defined as the process by which one mineral is substituted for another of differing chemical composition. This definition includes no theory as to the method of the replacement.

In his paper, "A Discussion of Metasomatism and the Linear 'Force of Growing Crystals,'"[1] Professor H. C. Boydell attempts to disprove the theory that pressure due to crystal growth is a factor in metasomatism and other geologic processes.

The fact, that under suitable conditions growing crystals may exert great pressure, has been repeatedly demonstrated by experiment, and references to "impossible perpetual motion" do not alter facts. Any doubter can easily convince himself by repeating some of the experiments which have been described. The mechanics of the process by which growing crystals exert pressure is, perhaps, debatable.

"So long as a crystal surface is in contact with a solution super-

[1] ECON. GEOL., 21, pp. 1–55, 1926.

saturated with respect to that surface, growth will continue no matter how great the pressure or strain may be." [2] In objecting to this statement, Professor Boydell (p. 8) appears to have a different conception of a supersaturated solution from that which is held by me. The effect of pressure on crystals of most substances is to increase their solubility, thus making a greater degree of concentration necessary in order to attain supersaturation and therefore crystal growth.

He invokes Le Chatelier's law (pp. 8 and 23) to prove that pressure would prevent crystal growth, but this applies only to a closed system in which concentration by circulation or diffusion from without is impossible and in which pressure is the only variable. Pressure does not prevent crystal growth, it merely increases solubility; and in spite of increased solubility growth will continue if supersaturation is maintained by increasing the concentration of the solution through cooling or any other method.

When magmatic solutions pass outward from an igneous intrusive into older rocks or upward along fractures, cooling is certainly one of the factors bringing about supersaturation and mineral deposition; but, if the pressure resisting crystal growth at a given point is such as to prevent supersaturation, crystal growth will not take place until the solutions reach a higher level where less resistance and further cooling of the solutions make it possible.

The supersaturation necessary for crystal growth under pressure may be brought about by any of the methods of inducing precipitation from solution, such as cooling and chemical reaction as well as evaporation. It is obvious that evaporation is not the cause of mineral precipitation in most cases, although it does bring about deposition of calcite to form the beds of *caliche* that underlie and displace the surface-soil at many places in Arizona, New Mexico, and other arid regions.

Pressure effects due to crystal growth are not limited to sub-

[2] Taber, Stephen, "The Mechanics of Vein Formation," *Trans. Amer. Inst. Min. Eng.*, 61, p. 29, 1918.

stances that go into solution with decrease in volume, for I have obtained similar results with several salts that enter into solution with increase in volume.

All crystals have developed under pressure; minerals crystallizing at great depth below the surface have necessarily grown under enormous pressure. In most cases, however, and especially in the formation of ore deposits by metasomatic processes mineral deposition probably takes place under less pressure than that existing at the points from which the ore-bearing solutions have come.

Pressure due to increase in volume accompanying alteration of anhydrite to gypsum is probably an important factor in the solution of part of the gypsum, which may then be deposited elsewhere forming the characteristic fibrous veinlets. Pressure is at a maximum where the gypsum is being formed and there the mineral is most readily taken into solution; it crystallizes out at points where the resistance to expansion is not prohibitive. I have suggested this as an explanation of the formation of chrysotile veins in association with the serpentinization of peridotite.

Growth of crystals under pressure is easier to explain than the method by which replacing solutions penetrate rocks, and yet we have abundant evidence that solutions have penetrated the densest rocks.

Professor Boydell quotes at length from Becker and Day, and emphasizes the fact that in their experiments the growth of crystals under pressure was confined to the exposed surfaces and to the periphery of the supporting face; and, that a sufficient "load may even cause resolution of the bottom surface while the side surfaces continue to grow." He then states that these "distinct limitations . . . would seem to have been quite lost sight of by advocates of the crystallizing force as a factor in vein formation" (p. 7). In his interpretation of this experiment Boydell makes essentially the same error as did Bruhns and Mecklenburg [8]

[8] Bruhns, A., and Mecklenburg, Werner, "Über die sogenannte Kristallisationskraft," 6th Jahresbericht d. *Niedersächsischen geol. Vereins*, pp. 92-115, 1913.

when they concluded that growing crystals can not exert pressure, because in their experiments the loaded crystals of alum placed in the same dish with unloaded crystals failed to grow in height.

It has been pointed out by Becker and Day and also by me that in the experiments of Bruhns and Mecklenburg their system was in unstable equilibrium due to the fact that loaded and unloaded crystals were in contact with the same solution. Similarly, where a single loaded crystal is growing in the solution, pressure is greatest on the base, since it supports the weight of the crystal together with any additional load; therefore, the supporting surface requires for growth a solution of greater concentration than is necessary in the case of faces subjected to less pressure. If the crystal is lifted by growth at the base it is due to the fact that during the process of supersaturation the denser portions of the solution tend to settle to the bottom and thus give a layer of higher concentration there than elsewhere.

The limitation of growth to the periphery of the supporting face of the crystal results in the formation of a cavity on that face and is due to the slow rate of diffusion under the crystal as compared with the relatively rapid growth on exposed faces. The development of this cavity was prevented in some of my experiments by supporting the crystal on porous material so that diffusion through the pores could maintain supersaturation under the crystal. It may also be prevented in other ways, such as by using very small crystals.

Professor Boydell thinks it incumbent on me to show that the openings through which the solutions diffused would not form avenues of relief for the system from the growing pressure (p. 8), but I have already done this in many experiments; the pressure effects would not be observed if the openings through which the solutions found access served as avenues of relief.

He also fails to understand why the pore spaces are not clogged by deposition (p. 22). Crystals that continue to grow after coming in contact with other solids must either displace these

solids or grow around them; and the size of openings occupied by the solution furnishing material for growth seems to be the most important factor in determining whether inclusion or exclusion shall occur. As stated in earlier papers, crystallization is retarded or prevented in supersaturated solutions which occupy small capillary or subcapillary spaces. Boydell suggests that Taber "has assumed this increase of solubility [in small pore spaces] in connection with his experiments," but he is mistaken. My statement, instead of being an assumption, is based on experiments that prove it. Several of these experiments were described in my paper "The Growth of Crystals Under External Pressure."[4] In fact, most of the objections raised by Boydell have been discussed either in that paper or in a later one entitled "Pressure Phenomena Accompanying the Growth of Crystals."[5] It is true that I made no reference to Thomson's work, but I did refer to the earlier work of Sorby.

The hypothesis that size of pore space is an important factor in determining the presence or absence of inclusions in crystals (*i.e.*, in determining whether the growing crystals shall displace the solution occupying the openings or displace the surrounding solids) is also supported by the occurrence of the so-called sand crystals of halite, gypsum, calcite, barite, etc., in material having relatively large interstitial spaces while practically pure crystals of these minerals develop in clays and shales where the pore spaces are small.

Professor Boydell states that it is incumbent on me "to explain the absence of columnar, acicular, and fibrous structure from the resultant vein material of many mineral deposits" (p. 64). Laboratory experiments, which have been described in several of my papers, prove that fibrous veins result when the crystals are in contact with a supersaturated solution only at their base, the solution being supplied through closely spaced capillary or subcapillary openings in the wall material; that non-fibrous

[4] *Amer. Jour. Sci.* (4), vol. 41, pp. 544–548, 1916.
[5] *Proc. Nat. Acad. Sci.*, vol. 3, pp. 297–302, 1917.

veins develop when the vein-forming solutions diffuse wholly or in part between the walls and therefore come in contact with the growing crystals on more than one side. I have also cited in some detail evidence in support of this theory as an explanation of the origin and structure of certain fibrous and non-fibrous mineral veins.[6]

Fibrous or acicular structure in minerals is, of course, due to several different causes. Many spheroidal crystalline growths show a more or less well-defined, radial, fibrous structure, but the explanation is obviously quite different from that of cross-fiber veins. I agree with Professor Boydell that the radial fibrous structure is not necessarily indicative of a colloidal origin. The anthophyllite of Sall Mountain, Georgia, shows this structure, and it seems to have been formed chiefly through the alteration of enstatite, the change being paramorphic.[7]

Metasomatism may take place without definite chemical reactions as a result of the solution of one mineral and the deposition of another in its place, but these two processes appear to be essentially simultaneous. It is inconceivable that two processes could be so closely synchronized unless they are in some way interdependent, and I have previously suggested that this would occur (1) if solution of the replaced mineral induced deposition of the replacing mineral or (2) if the latter forced the former into solution. In both cases the volume of the replacing mineral is equal to the volume of the mineral replaced.

These two methods apparently explain the two ways in which silica is found replacing calcite. Silica, usually amorphous or cryptocrystalline, forms pseudomorphs after calcite and replaces the calcium carbonate of fossil shells and coral in such a way as to preserve the microscopic details of structure. Calcite is also replaced by silica in the form of large idiomorphic crystals of quartz.

[6] "The Origin of Veinlets in the Silurian and Devonian Strata of Central New York," *Jour. Geol.*, vol. 26, pp. 56–73, 1918.

[7] Hopkins, O. B., "Report on the Asbestos, Talc and Soapstone Deposits of Georgia," *Geol. Surv. Georgia, Bull.* 29, p. 104, 1914.

The first type of replacement seems to be proved by the experiments of Cox, Dean, and Gottschalk, who found that silica can be precipitated from colloidal solutions by calcite when $CO_2$ is present, because of the positively charged calcium ions of the dissociated calcium bicarbonate.[8] Since the precipitation of the silica is due to the solution of the calcium carbonate, the structure of the latter may be preserved. It is suggested that preservation of structure may be a criterium for the recognition of colloidal replacement.

In the second type of replacement all evidence of structure is destroyed by the growth of the crystal. When a mineral crystal in growing exerts pressure on the older surrounding minerals, they may be mechanically displaced, or, because of increase in solubility with pressure, they may be forced into solution and removed.

Since enormous pressure would be required to make room by mechanical displacement for a crystal growing in compact rock at depth below the surface, and, since the solubility of most substances, so far as known is increased by pressure and strain, the space necessary for crystal growth is usually obtained either wholly or in part through solution of the surrounding minerals. I know of no hypothesis that will explain well-developed crystal form in metasomatic minerals except that the crystals in growing have exerted pressure on the surrounding material, thus causing its removal in solution.

In recent years we have learned that colloidal solutions are a factor in several geologic processes. They are probably of considerable importance in metasomatism, especially under near surface conditions, but, as yet, little evidence has been adduced in support of this hypothesis for the deeper zones where pressure and temperature are high. Colloidal particles are, as a rule, much larger than ions or molecules, and therefore could not diffuse through very small openings that would be permeable for true

[8] Cox, G. H., Dean, R. S., and Gottschalk, V. H., "Studies on the Origin of Missouri Cherts and Zinc Ores," *Bulletin of the School of Mines and Metallurgy, University of Missouri*, vol. 3, pp. 5–34, 1916.

solutions. Dense rocks and ores, in which the openings are very small, would behave much as semi-permeable membranes. Metasomatism may take place in the densest rocks.

Also there is much evidence that during the last stages in the formation of some pegmatites as well as veins, minerals are deposited from solutions that penetrate along the contacts between the minerals rather than through appreciable openings, the new minerals replacing, or, in some cases, displacing the earlier minerals.

The high penetrativeness of some replacing solutions, the composition of some of the minerals formed, and other evidences of high temperature indicate that the solutions are sometimes gaseous; but Boydell eliminates gas as a factor in metasomatism without citing any evidence other than the *tendency* of pressure to suppress a gas phase (p. 4).

Professor Boydell adopts Lindgren's theory that in solid rocks the volume of the replacing mineral is equal to that of the mineral replaced, and concludes " that the reaction involved in such a case does not take place in simple molecular ratio, *i.e.,* in the quantitative proportions of the chemical equation representing the reaction " (p. 5). I believe that one mineral may replace another without chemical reaction by the two methods explained above, but where replacement is the result of a chemical reaction, a definite number of atoms is added, subtracted or interchanged, the number depending on the quantity of the mineral replaced and the nature of the reaction. Of course, this statement applies to a system that as a whole is three-dimensional and not two-dimensional.

In many cases of replacement, because of lack of knowledge, it is impossible to write chemical equations, but for certain alterations the equations are simple. Lindgren specifically includes alteration under metasomatism.[9]

The alteration of magnetite to hematite or limonite and of anhydrite to gypsum, clearly involve an increase in the volume

[9] Lindgren, Waldemar, " Metasomatism," *Bulletin Geological Society of America,* vol. 36, p. 248, 1925.

of mineral matter, and, if the alteration takes place within a rock mass, pressure must be developed.

This may be demonstrated experimentally by exposing a porous porcelain cell containing an anhydrous salt to moist air. Water vapor penetrates the pores of the cell, and the increase in volume due to hydration results in pressure which ruptures the cell. Glass bottles with walls 1.5 to 3.25 millimeters in thickness have been broken in this way by the hydration of zinc nitrate. Pressure due to hydration cannot be attributed to a chemical reaction taking place with expansion in total volume, for the volume of the hydrated salt is commonly less than that of the anhydrous salt plus the water of hydration. The pressure results from the increased volume of the solid due to the fact that water in liquid or gaseous state penetrates the porous enclosing material, while the new crystals formed do not escape in like manner.

When the new mineral is greater in volume than the mineral replaced, the surrounding minerals may be mechanically displaced, or, more commonly, the pressure due to expansion in volume will force into solution either a part of the new mineral or a part of the surrounding minerals, and thus remove enough material to compensate for the increase in volume. The replacement of anhydrite by gypsum, referred to above, is an illustration.

The replacement of individual minerals within a rock, therefore seldom changes the volume of the rock mass, but, if all of a rock or a considerable part of it, undergoes alteration as in some cases of serpentinization, there may be an increase in the volume of the mass.

Internal slickensides and slip-fiber chrysotile, so characteristic of massive serpentine are commonly explained by expansion in volume. Crosby [10] has attributed the elevation of the Staten Island serpentine stock to this cause, and Heddle [11] has called attention to similar occurrences.

[10] Crosby, W. O., "Physiographic Relations of Serpentine with Special Reference to the Serpentine Stock of Staten Island, N. Y.," *Journal of Geology*, vol. 22, pp. 582–593, 1914.

[11] Heddle, M. F., "Chapters on the Mineralogy of Scotland," *Transactions of the Royal Society of Edinburgh*, vol. 28, pp. 453–555 (1876–1878).

When the replacement of one mineral by another results in a decrease in volume, the new mineral is commonly porous or cellular in structure as is well illustrated by many pseudomorphs of native silver after argentite and of smithsonite after calcite. In some cases the voids are filled through deposition of other minerals.

A specimen of fine grained schist from near Columbia, S. C., contains a cubical crystal of pyrite with smooth faces 2 centi-

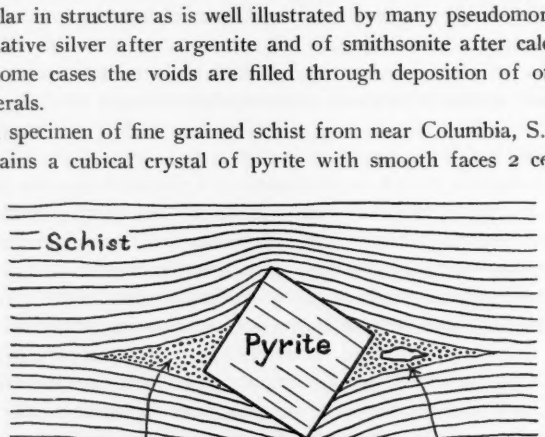


FIG. 1. Pyrite crystal partly replacing and partly displacing the laminae of a fine-grained schist.

meters square (see Fig. 1). The cleavage laminæ of the schist are bent outward opposite the crystal of pyrite, but some of them terminate abruptly against it, thus proving that the crystal has made room for itself by partly replacing and partly displacing the schist. The annular space around the pyrite where the cleavage laminæ have been separated is largely filled with quartz crystals which show a tendency to elongation in directions radial to the pyrite. At one place, however, the filling with quartz is incomplete, leaving a cavity, 2 millimeters by 3 to 4 millimeters, within which the quartz shows crystal faces.

In this case the growing pyrite crystal must have exerted pressure to displace adjacent minerals, but whether the rock

mass as a whole increased in volume depends on the source of the material in the crystal. If the boundaries of a rock mass undergoing metasomatism are considered to extend far enough to include the source of the new material that is introduced in solution, then there can be little or no increase in the volume of a rock mass except through such alterations as oxidation and hydration.

Conclusion: It has been proved that growing crystals may exert pressure and that pressure may be developed by chemical reactions resulting in an increase in volume of solids. Such pressure must be a factor in metasomatism, since the solubility of many substances is increased by pressure. The relative importance of this factor in metasomatism and other geologic processes must be decided by the geologic evidence. Those who oppose the theory that pressure due to crystal growth is of importance in geologic processes should show that some other theory will better explain the facts.

STEPHEN TABER.

UNIVERSITY OF SOUTH CAROLINA,
COLUMBIA, S. C.

## *WOOD TIN—GEL REPLACEMENT OF CASSITERITE.*

*Sir:* Attention has recently been drawn by Dr. H. C. Boydell[1] to the paper by A. Knopf on "Wood Tin in the Tertiary Rhyolites of Northern Nevada,"[2] in which that author arrived at the conclusion that the *wood tin* and some of the accompanying minerals, such as opal and chalcedony, were deposited as colloids. Although Dr. Boydell differs from Dr. Knopf as to the cause of the banding, he apparently agrees with the idea of colloidal deposition. The latter is of special interest to the writer, in view of certain observations made by him, in examining thin sections of the ores of the well-known cassiterite pipes situated north-northwest of Potgietersrust in the central Transvaal, which indicate that cassiterite can be replaced by silica gel.

[1] ECON. GEOL., No. 8, vol. 20, 1925, pp. 768–770.
[2] ECON. GEOL., vol. 11, 1916, pp. 652–661.

The Potgietersrust cassiterite pipes, of which good descriptions have been published,[3] are essentially tubular bodies of altered mineralized granite in coarse red granite, formed mainly by replacement and to a less extent by cavity filling. Evidence collected by the writer during the past five years renders it probable that they have developed from trains of tubular and lenticular miarolitic zones in the granite comparable with the trains of bubbles often observed in glass melts, but further evidence is required to prove the theory. If it should prove correct, it would be necessary from the nature of the ore to assume that certain of the postulated miarolitic zones were richer in feldspar than the normal red granite. The pipes have had a complex history, and it is probable that, as in other South African tin deposits, successive generations of minerals have replaced one another. Their formation may be divided into four stages, namely:

(1) *Pneumatolytic or High Temperature Stage.*—Deposition of cassiterite, tourmaline, scheelite, specularite, magnetite, arsenopyrite, accompanied perhaps by some sericite.

(2) *Early Hydrothermal or Intermediate Temperature Stage.*—Deposition of quartz, sericite, chlorite, pyrite, chalcopyrite, fluorspar.

(3) *Late Hydrothermal or Low Temperature Stage.*—(*a*) Deposition of chlorite, ankerite, calcite, zincblende, galena and native bismuth. (*b*) Deposition of colloidal silica and solution of cassiterite.

Cassiterite, which occurs in well-formed pyramidal crystals averaging between 1.5 and 2 millimeters in diameter, was the first mineral to be deposited.[4] It was introduced mainly as a result of the replacement of the original quartz of the granite and

[3] Kynaston, H., and Mellor, E. T., "The Geology of the Waterberg Tinfields," Memoir No. 3, Geol. Survey of the Transvaal, 1908.

[4] It is maintained by some geologists, who have studied the deposits, that the deposition of cassiterite was preceded by that of red feldspar which replaces both the original feldspar (microperthite composed of red orthoclase and oligoclase) and the original quartz of the granite. The thin sections so far examined by the writer afford no conclusive evidence on this question.

of quartz crystals in miaroles in that rock. It also replaces feldspar. There is clear evidence, however, as has been pointed out elsewhere,[5] that cassiterite replaced quartz in preference to feldspar in these deposits; a possible explanation being the similarity in specific volume of the two minerals.

The colloidal silica, now represented by chalcedony and quartz, the deposition of which was the final act in the formation of the deposits, is confined to certain of the pipes on the farms Groenfontein No. 871 and Salomons Temple No. 1014, and to the No. 3A pipe on Zaaiplaats No. 236. It was, however, also noted in one of the deposits on Mutue Fides, situated sixty miles south-southeast of the Potgietersrust tin fields.

The interior of some of the smaller pipes on Groenfontein and Salomons Temple is occupied entirely by dense, cryptocrystalline chalcedony, grey or dirty brown in color. The chalcedony is sometimes beautifully banded and in places exhibits a concentric zonal structure similar to that seen in agate. It thus shows distinct evidence of its gel origin. Thin sections prove that it consists of an aggregate of minute grains and fibres of chalcedony, interspersed with small grains of quartz and aggregates of such grains, representing a further stage in the crystallization of the silica gel. Shreds of pale yellow sericite are also generally in evidence, but it is not clear whether these are contemporaneous with the chalcedony or are part of the earlier-formed pipe filling.

Chalcedony of the same type is present in the hanging wall section of the No. 3A pipe on Zaaiplaats. In a thin slice of the chalcedonic ore of that occurrence, well-formed crystals of cassiterite, which in one part of the slice replace early-formed quartz crystals, are seen in process of replacement by chalcedony and quartz that has evidently been derived from the chalcedony. The replacement is even better seen in a thin slice from the same type of ore from the No. 10 pipe on Groenfontein. Here long parallel tapering fingers of chalcedony and quartz have eaten into the cassiterite, the peculiar banding of that mineral and cleavage

[5] ECON. GEOL., vol. 18, 1923, p. 697.

cracks in it being still seen in their original position on opposite sides of such fingers. Some of the crystals are in an advanced stage of replacement and there is no reason why, under favorable conditions, the replacement should not have been complete.

This might explain why many of the smaller pipes on Salomons Temple, in which chalcedonic silica is very much in evidence, are practically barren of tin.

Another interesting possibility suggests itself. The replacement of cassiterite by silica gel and the complete removal of the replaced stannic oxide appears necessarily to imply that the stannic oxide went into colloidal solution in the siliceous hydrosol that brought about the replacement. It is conceivable that the dissolved stannic oxide may have been deposited at a higher level in the original upward continuation of the deposits in question, or in fractures in the rock at one time overlying them, as wood tin, associated with opal, thus reproducing the conditions noted by Knopf.

This is mere speculation. The important point is that we have an illustration of gel replacement, a process the importance of which has recently been emphasized in so illuminating a manner by Professor Waldemar Lindgren.[6]

A final word on the probable nature and temperature of the replacing solutions: these were evidently highly siliceous thermal waters. The shreds of sericite asociated with the chalcedony suggest that they may have contained potassa and alumina, but as already pointed out, the sericite may belong to an earlier stage of mineralization. It is highly probable, however, that they were alkaline, as it is difficult to conceive of a pure silica solution attacking so insoluble a mineral as cassiterite.

As to the temperature of the replacing solutions, this must have been considerably lower than that responsible for the mineralization during stage III*a*. In some pipes there are found breccias in which angular fragments of the minerals formed during that stage are found imbedded in chalcedonic silica, indicating

[6] "Gel Replacement, A New Aspect of Metasomatism," *Proc. Nat. Acad. Sci. Washington*, vol. II., 1925, pp. 5–11.

that a considerable interval elapsed between stages III*a* and III*b* in which the minerals formed during the earlier period underwent fragmentation. Taken in conjunction with the nature of the minerals deposited during stage III*a*, this renders it doubtful whether the temperature of the colloidal siliceous solutions could have been much higher than 100° C, and it may have been lower.

PERCY A. WAGNER.

GEOLOGICAL SURVEY OFFICE,
PRETORIA, SOUTH AFRICA.

# REVIEWS

**Magmatic Nickel Deposits of the Bushveld Complex in the Rustenberg District, Transvaal.** By PERCY A. WAGNER. Pp. 181, plates 22, Figs. 14. Union South Africa, Dept. of Mines and Industries, Geol. Surv. Mem. 21.

Dr. Wagner's Memoir is a study of the norites and ultra-basic rocks with associated deposits of copper and nickel sulphides of the Bushveld Complex in the Transvaal. Much of the paper is of a petrographic nature, more space being devoted to descriptions of the rocks than to the ore deposits. This is perhaps as it should be since an understanding of the genesis of the ores can come only through familiarity with the chemical and physical relationships of the associated basic rocks.

The nickel deposits are within the main mass of the sagged laccolith or lopolith that was intruded into the sedimentaries of the Pretoria series of the Rustenberg district of the western Transvaal. A composite section of the lopolith indicates an approximate thickness of some 15,000 feet divided, on petrographic grounds, into upper and lower portions. The upper 8,000 feet is made up mainly of diallage norite grading above into syenite. Within the norite are stratiform segregations of titaniferous magnetite and labradorite anorthosite. The lower portion of approximately 7,000 feet consists of nearly undifferentiated norite at the top; below is a series of highly differentiated basic rocks the greater part being bronzitites with dunites and pyroxenic olivine norites. At the lower contact certain marginal hybrid types, such as diabasic quartz norites, frequently occur. Many of the rock bodies show a distinct pseudostratification that is at present inclined from the horizontal but that, before the sagging of the laccolith, is believed to have conformed closely to the stratification of the invaded sedimentaries.

The copper-nickel deposits unlike those of Sudbury and Insizwa occur some 4,000 feet above the base of the laccolith. They do not form large continuous ore bodies but rather lenses or irregular masses in the norite differentiates over an area of about six square miles. Throughout the rocks of the differentiated zone, blebs of metallic sulphides are present, usually in interstitial relationship to the other minerals, and, in the neighborhood of ore bodies, all gradations are found between rock spotted with sulphides to massive ore enclosing crystals of bronzite and biotite. The primary ore minerals consist of the usual pyrrhotite, chalcopyrite and pentlandite with which are lesser amounts of pyrite, chromite, magnetite,

sperrylite, the platinum metals, gold, and silver. The abundance of marcasite in association with the primary minerals is noteworthy, and of particular interest is graphite that is universally present in the ore bodies and in the sulphide bearing bronzitites immediately in their vicinity. In addition to the primary ore minerals are others clearly of later origin.

Speculation as to the origin of the sulphide deposits involves a consideration of the general petrology of the region. Without attempting to go into details, however, Wagner's interpretation may be summarized briefly. The original magma is considered to have been a norite. Differentiation began at an early period after intrusion through the crystallization of certain constituents, notably the pyroxenes, and their segregations through the influence of gravity near the bottom of the laccolithic chamber, resting on a zone of norite and hybrid rocks at the lower contact. For reasons that need not be discussed here, there appears to have been in the crystallization of the magma, a sort of rythmical alternation of magnesium-rich bronzitites and calcic norites or anorthosites. The gradual concentration of magnesia in the residual magma through the separation of the calcic feldspar is believed to have finally brought about conditions favorable for the precipitation of the sulphides. The sulphides did not begin to separate from the magma until later, coming down with the magnesium-rich bronzitite and forming local segregations. The influence of mineralizers, notably sulphur, perhaps in the form of $H_2S$, is regarded as largely responsible for the sulphides remaining in solution as long as they did. The common presence of graphite in both ore and rock is a remarkable feature of the deposits. The much lower melting points of the sulphides suggest that, in the larger accumulations, they remained liquid for considerable periods after the consolidation of the surrounding rocks and that in this way many of the vein-like bodies occupying fractures in the rocks and frequently terminating downward are to be accounted for.

Associated with the massive deposits are veins of pyrite and siderite attributed to a later hydrothermal origin of a local nature due to the liberation of $CO_2$ and $H_2S$ by the cooling rocks and sulphides. Marcasite as a secondary mineral after pyrrhotite is a striking characteristic of the Vlakfontein ores and is believed to have been formed by the action of $H_2SO_4$ and ferric sulphate derived from the oxidation of sulphides above water level.

The paper is a valuable contribution to the literature of magmatic ores and deserves the attention of all students of this interesting type of deposits.

ERNEST HOWE.

LITCHFIELD,
CONNECTICUT.

**Die Diamantenwüste Südwest-Afrikas.** By ERICH KAISER. Dietrich Reimer, Berlin, 1926. In 2 quarto volumes, pp. x + 321 and vii + 535, with 13 maps, 56 plates, 158 text figures and 32 stereoscopic views in pocket.

In the truly magnificent work described above, Dr. Kaiser, who has devoted his attention chiefly to the general geology and to the petrology of the igneous rocks, has had the collaboration of W. Beetz (topography and general geology), J. Böhm (Tertiary fossils), R. Martin (anthropology). H. Rauf (freshwater Tertiary), M. Storz (secondary siliceous rocks), E. Stromer (vertebrate fossils), W. Weissermel (Tertiary corals), W. Wenz (Tertiary mollusca), and K. Willmann (petrography).

The region described is a portion of the desert coastal belt that extends from Cape Colony northward for over 800 miles and is known to South African geographers by its Hottentot name, the Namib. The particular section with which this monograph is concerned is near the southern end of the belt and extends from the vicinity of Elizabeth Bay, on the north (latitude 27° S.) for a distance of about 50 miles to the south. The region, barren, windswept and inhospitable as it is, was by no means unknown prior to the work of Dr. Kaiser. A good description by Wagner [1] was published in 1916 and contains a bibliography of 122 entries of earlier papers relating more or less closely to the geology of Southwest Africa. The discovery of diamonds in 1908 focussed considerable attention upon the southern Namib and the general sequence and character of the geological formations had been fairly well determined before Dr. Kaiser entered the field, as may be seen from the reconnaissance map compiled by Wagner to accompany his report.

Beetz and Kaiser have mapped the country studied by them on a scale of 1 : 25,000, with 10-meter contours, and have outlined the geological formations on this base with surprising detail. This geological map is in itself a remarkable achievement in view of the extremely arid and very sparsely settled character of the region. In addition, the monograph is accompanied by 7 special maps on various scales.

In a general way, the region described slopes upward from the coast to the western border of the interior plateau of South Africa. In detail, it presents a succession of generally short ridges and detritus-floored valleys that run roughly parallel with the coast. The relief is moderate, only a few parts of the area rising more than 700 feet above the sea. In some localities, the parallel ridges give place to scattered buttes and mesas.

A fundamental complex of schists, gneisses, granites, and basic eruptives, is unconformably overlain by the Konkip formation, chiefly quartz-

[1] Wagner, P. A., "The Geology and Mineral Industry of Southwest Africa," Union of South Africa Mines Dept., Geological Survey Memoir No. 7. Pretoria, 1916.

ite and dolomite of undetermined age. Unconformably above the Konkip formation lie the basal conglomerate and succeeding quartzites, dolomites and shales of the Nama system, which is provisionally regarded as Cambrian. This formation, which has been folded in general parallelism with the coast, is said to be in places fully 3,000 feet thick.

Apparently post-Jurassic but probably pre-Tertiary in age, is an interesting group of alkali-rich igneous rocks, including nepheline syenite, alkali granite, syenite porphyries, bostonite, tinguaite, phonolite, and mellilite basalt.

A series of sedimentary rocks, predominantly sandstones, is considered to be probably Cretaceous.

Tertiary beds are described under the headings "Pre-middle Eocene," "Middle and Upper Marine Eocene," and "Post-Eocene beds."

The Quarternary deposits, including gravels, residual sands, fanglomerates, dunes, etc., are mapped in great detail and fully described.

The nepheline syenite occurs as two large intrusive stocks surrounded by aureoles of bostonite, tinguaite, and syenite porphyry dikes. One of these stocks and its associated dikes, that of Granite Mountain (Granitberg), was mapped in detail and the rocks are fully described, with many chemical analyses that are apparently of excellent character.

The greater part of the first volume is occupied with the description of the rocks of the fundamental complex, an account of the pre-Tertiary sedimentary formations, the petrology of the syenitic rocks and their associated dikes, and the structure of the region. In the structure, faulting has played a prominent part and one of the most conspicuous tectonic features of the region is the occurrence of a number of large downfaulted blocks or *graben*. The eruption of the syenitic-foyaitic magma is believed to have been a consequence of the sinking of these fault blocks.

The second volume is devoted chiefly to the description of the Tertiary and Quaternary deposits, a discussion of the morphogeny of the present land surface, and special reports on paleontology, anthropology, etc.

The only important economic resource of the region, diamonds, is rather briefly treated in about 15 pages.

The diamonds of the Namib occur solely in detrital material. Discovered in 1908, the deposits in 1913 yielded 20 per cent. of the total diamond output of the world for that year. Diamonds have been found occasionally in the Tertiary sandstones and somewhat more abundantly in some of the older Quaternary detrital deposits (fanglomerates) but these occurrences are not of economic character. The workable deposits are principally the residual sands and detrital material (*Schutt*) that lie on the floors of the desert valleys and, to a less extent, the late Quaternary alluvial fans (fanglomerate) that flank some of the ridges. Water and wind, especially, in the later stages, wind, have coöperated to concentrate

the diamonds from their original condition of sparse distribution in the Tertiary sandstones to deposits, some of which have been extraordinarily rich, lying on the surface of the valleys. In these valleys the strong south-southwest winds have winnowed away the lighter, smaller, and more readily disintegrated particles, leaving behind on the actual surface a natural diamond concentrate. In some valleys the diamonds themselves have been blown along and concentrated at the north end of the valley or on the windward side of projecting rock ledges. The stones are of all weights up to 35 carets and of various colors, although brilliant white or slightly yellowish gems predominate. Kaiser maintains that most of the diamonds are very little worn and still retain their sharp crystal edges. In this he differs somewhat from Wagner and other observers.

The diamond-bearing sand is commonly worked by hand methods, although in a few places electrically driven shovels are used, particularly where the diamonds are obtained from alluvial fan deposits, in which excavation may be carried to depths of 20 to 30 feet.

Although the richest ground is believed to have been exhausted, Dr. Kaiser maintains that production is likely to continue for many years from the lower-grade deposits.

The original source of the diamonds is unknown.

The two volumes that contain this very substantial by-product of scientific diamond prospecting in Southwest Africa are beautifully printed and illustrated and strongly bound in heavy cloth. They are distinctly a credit to their publisher.

F. L. RANSOME.

**Iron Ores: Bedded Ores of England and Wales,—Petrography and Chemistry.** By A. F. HALLIMOND, with an appendix by F. R. ENNOS and R. SUTCLIFFE. Memoirs of the British Geological Society, Special Reports on the Mineral Resources of Great Britain, Volume XXIX., 1925, pages 139, plates I.–VIII., figures 3.

This volume summarizes existing knowledge as to the chemistry and mineralogy of the chief English and Welsh bedded iron ores, and is of special interest to American geologists because many of the deposits described resemble the protores of the Lake Superior region and yet are, as the author rightly remarks, free from the general metamorphic changes which the latter have suffered. In North America their nearest counterpart would be the chamosite-hematites of Wabana.

The author classifies the sedimentary iron ores as follows: Ferrous ores —I. Chamosite and chamosite-siderite mudstones. II. Siderite mudstones—non-chamositic. III. Sideritic limestones.

Ferric ores—IV. Ferric chamosite oölites (among which are placed—

incorrectly—the Clinton ores). V. Limonitic oölites. VI. Primary hematites. VII. Glauconitic rocks (commercially valueless). Pyritic ores, though described, are omitted from this table. All these sediments are clearly marine or estuarine, as indicated by their fossils.

Physically the most striking observation is the general presence of features indicating erosion and redeposition, such as breccias and the excellent sorting of oölites on the basis of size.

As to the mode of precipitation, reference is made to the well-known solubility product principle of Nernst. The solubility curve for siderite is similar to that for other carbonates, and calcium carbonate is taken as an example, the basis being studies made in the Geophysical Laboratory at Washington. Solubility of carbonates is a function of the partial pressure of carbon dioxide above the solution, and decreases at first with increase in pressure until a pressure-value equal to about one one-hundredth of that in the atmosphere is reached; beyond this point the solubility rises again with increase in the pressure of the gas, because the bicarbonate is formed and the quantity of $CO_3$ ions correspondingly reduced. If the pressure of the gas is only slightly varied in the neighborhood of the point where the saturation curve changes direction, calcium carbonate can be made to precipitate or dissolve at will.

The same principle is applied to the precipitation of siderite. Some siderite is genetically of this type,—a primary precipitate induced by the decrease in the partial pressure of carbon dioxide; but much is referable to an alteration of chamosite, during consolidation or subsequently, the vadose circulation in part perhaps facilitating the change. The "black band" ores, similar to the siderites of the American Coal Measures, are probably cases of precipitation from exceptionally acid waters, the carbon dioxide being removed by plant action or evaporation.

Chamosite, essentially a protore, is regarded as a precipitate from a muddy sea whose waters, if rich in iron, are virtually a saturated solution of iron salts and clay. Here the solubility product principle is again invoked; even relatively small amounts of iron produce precipitation of equivalent parts of hydrated $3FeO \cdot Al_2O_3 \cdot 2SiO_2$ (chamosite). This and the formation of siderite may go on side by side. If the ferric oxide-alumina ratio in the solution is greater than 1 to 3, free limonite is deposited, appearing as oölite or, under highly oxidizing conditions, as red mud. Exceptionally thuringite is formed instead of chamosite.

In all these types of precipitation bacteria, as suggested by Harder, or algæ may also have played an important part, and "algues perforantes," apparently similar to those described by Hayes from the Wabana ores, are repeatedly mentioned.

Weathering produces effects like those found in the Clinton deposits of the United States,—oxidation and hydration, as well as residual enrichment by the leaching of calcium carbonate if the latter is present. Nothing in these statements furthers the concept of Van Hise in regard to enrichment in the Lake Superior ores by large-scale transfer of iron carbonate with subsequent deposition in that form.

The report contains 42 photomicrographs of the ores, many of which furnish excellent illustrations of zoning in oölites. An appendix discusses methods of estimating the chlorite in sedimentary rocks.

A description of the general geologic relations of the ores is not undertaken in the 120 pages of text. As a summary of the mineralogy and chemistry of the British bedded iron deposits, however, the paper leaves little to be desired. It is a distinct contribution to the rapprochement of physical chemistry and ore genesis.

CHAS. H. BEHRE, JR.

UNIVERSITY OF CINCINNATI.

**A Résumé of Arizona Geology.** By N. H. DARTON. Pp. 298, illustrated. Ariz. Bur. of Mines, Bull. 119. Tucson, 1925. Price $1.00.

Readers interested in Arizona areal geology will find in this bulletin an invaluable summary and reference work. Made possible through a cooperative agreement between the U. S. Geological Survey and the Arizona Bureau of Mines, the résumé was undertaken as an explanatory companion-piece to the geologic map of Arizona recently issued. The author, besides having had extensive field experience in Arizona, has had access to many unpublished data relating to the geology of the state. The available information is necessarily far more detailed in some parts of the state than in others, and yet the information here presented is remarkably full. In very few cases are local descriptions incomplete because of lack of knowledge.

The bulletin is divided into two parts. The first deals with the entire stratigraphic succession, describing each formation and bringing up to date the classification of each. The second part is devoted to an areal discussion of the geology of various districts, arranged by counties. Details from published reports are generalized as far as possible, so that the greatest possible amount of new material may be made available. No controversial discussions are entered into, the opinions expressed being frankly those of the author. No detailed reference is made to ore deposits, the data relating entirely to areal geology. The bulletin is helpfully and intelligently illustrated with 72 plates and 105 figures, the former being maps and the latter including both photographs and geologic sections.

RICHARD FOSTER FLINT.

**The Surface History of the Earth.** By JOHN JOLY. Pp. 192, 13 plates, 11 text figures, and map. Oxford, 1925. (Oxford University Press, $3.00.)

Professor Joly attempts to explain the cyclic and recurrent events in the geologic record with a modern hypothesis based jointly on isostasy and radio-activity. Briefly, his argument is as follows:

The great basalt flows consist of primary magma, and indicate the presence of a basaltic substratum beneath the continents and ocean basins. Both the folded mountains commonly along the continental borders, and the tensional effects (such as the great Rift Valley of Africa) are the result of forces coming from great depths.

Isostasy is taken as well substantiated fact. The granitic continental areas are considered to be buoyant crust segments approximately 20 miles in thickness, floating (largely submerged) in the basaltic substratum. The well-nigh universal evolution of radioactive heat by igneous rocks is brought forward, and the substratum is shown to be thus accumulating heat which is not given off into the overlying continental masses. Thus within a period computed to be approximately 33,000,000 years, melting would result; the attendant decrease in density permitting the continents to sink deeper into the sustaining substratum, with gradual encroachment of the seas upon the continental surfaces. With the increase in volume caused by melting, the solid crust becomes too small to fit an expanding interior, hydrostatic pressure is set up, and tensile stresses in the crust result in rifting and the extrusion of basic magma. The liquefaction of the substratum makes it subject to tidal strains, which result in a slow shifting of the entire outer crust in a westerly direction. This shifts the relatively thin ocean floors gradually over areas previously covered by the continents, thus allowing successive equal radiation of heat through the ocean, from the entire surface area of the substratum. The ocean absorbs the accumulated heat and the cooling magma slowly solidifies from beneath upwards (due to convection), thus causing the tidal effect gradually to die out. The substratum contracts to its former size, and as the continental masses are slowly pushed up to their original levels, the epicontinental seas slowly withdraw. But the crust having gradually become too great for the shrinking interior, the oceanic segments crowd upon the continental margins and localize the development of folded ranges from the geosynclines, formed during the slow continental downsinking in the earlier part of the cycle. The igneous activity associated with orogenic movements is cited as proof of the depth in the continental mass to which the horizontal forces extend.

In the discussion of the revolutions themselves, it is pointed out that the observed variability of these periods of stress can be accounted for by variations in the amount of the substratum liquefied, and by the rein-

forcement of a declining revolution by fresh supplies of heat from beneath. Erosion of the continents and deposition along their borders tends to widen the continental areas; compression exerted during the orogenic periods tends to narrow them. Thus, in the opinion of Professor Joly, an essential balance is maintained.

No comprehensive theory of the origin of the great earth movements has attempted to explain and to bring into clear relations so many widely different factors. Professor Joly has undertaken an immense piece of work, which quite aside from the clarity and limpidity of his style, and the careful masonry of his argument, must be greatly respected. Certainly there are points left unexplained, such as the exact reasons why ranges are not folded on both sides of a continent simultaneously; there are others, such as the attributing of climatic changes solely to vertical movements of the land, which many will wish to question at once. Yet it remains a valuable working hypothesis to be tested and checked against. Professor W. M. Davis has recently included Professor Joly's latest work in his category of "outrageous hypotheses": surely its very outrageousness renders it even more worthy of long and serious consideration.

RICHARD FOSTER FLINT.

# SCIENTIFIC NOTES AND NEWS

E. C. Andrews, Government Geologist of New South Wales, will deliver the Silliman lectures this fall at Yale University.

Sydney H. Ball and Allen H. Rogers have returned to New York City after two months in Peru.

A. C. Lawson has returned from a trip to Europe and South Africa and is now in Butte on professional business.

Augustus Locke, of San Francisco, has been in the East for the last month.

F. L. Ransome has completed his study of the properties of the Ahumada Lead Company in northern Mexico and is at present in Butte on professional business.

F. E. Calkins, of Globe, Arizona, is examining properties in Arizona and California.

Waldemar Lindgren, W. T. Mead, Alan Bateman and W. H. Wiley are at Butte, Montana, on professional business.

Louis E. Reber, Jr., is spending a year in Northern Rhodesia in work for the Rhodesian Congo Border Concessions Ltd.

Ernest Howe has been appointed by Yale University as editor of the *American Journal of Science*, and has taken over the active editorial duties previously carried temporarily by Alan Bateman. The latter remains as chairman of the Board in charge of the publication of the *Journal*. Professor E. S. Dana will continue part of the editorial duties.

B. S. Butler, of the U. S. Geological Survey, is doing special geological research work in Colorado in coöperation with the Colorado Metal Mining Fund.

S. R. Feldtman, of the Geological Survey of Western Australia, is studying placer mining conditions in the Cariboo district of British Columbia.

Guy C. Riddell, of New York, with E. D. Foster, of Los Angeles, has been spending four months in examining the principal oil shale deposits in California, and is making a similar survey in the Indiana-Kentucky-Tennessee region.

J. H. Horsburgh, assistant general manager of the Mount Morgan Company of Queensland, is chairman of a commission appointed by the Australian Federal Government for the development of North Australia.

L. C. Glenn, of Vanderbilt University, has been examining property in the rock asphalt region of Kentucky.

B. D. Stewart, supervising mining engineer for the U. S. Geological Survey in Alaska, is engaged in collecting authentic information as to the nature, extent and availability of the known mineral resources of the Territory.

Charles R. Fettke and F. A. Copeland, of the Carnegie Institute of Technology, have returned to Pittsburgh after a detailed geological survey of the oil fields of the Bradford Quadrangle for the Pennsylvania Geological Survey. Field work will be continued next summer.

Chester R. Thomas has left the Amerada Petroleum Company and opened an office as consulting geologist at 314 Clinton Building, Tulsa, Oklahoma.

H. W. Turner, of Urbana, Illinois, was in Wyoming during September engaged in professional work.

A. N. McIntosh, geologist, recently connected with the Mazapil Copper Company, Ltd., of Coahuila, Mexico, has returned to Canada.

W. F. Prouty, professor of economic geology at the University of North Carolina, has been spending some time in the southern Appalachians investigating possible sources of ornamental building stone.

Robert J. Anderson, metallurgical engineer, has opened a commercial testing laboratory, specializing in metals and alloys, at Cincinnati, Ohio.

J. C. Murray, mining engineer, died on September 28th at Tangier, N. S., aged 52 years. He was a graduate of Dalhousie and Queens University, Kingston, and was formerly editor of the *Canadian Mining Journal*.

Edward D. Nolan, chief geologist of the General Petroleum Corporation of Los Angeles, died in San Francisco on September 5th at the age of 36, following a brief illness. He was well known throughout the United States as a petroleum geologist.

The 22d Annual New England Intercollegiate Geological Excursion took place at New Haven, Connecticut, on October 8th and 9th.